Electrification of the Transportation System

An MIT Energy Initiative Symposium

April 8, 2010

Massachusetts Institute of Technology

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ABOUT THE REPORT

Summary for Policy Makers

On April 8, 2010, the MIT Energy Initiative (MITEI) sponsored a symposium on: *The electrification of the transportation system: issues and opportunities*. The symposium was organized into four panels that addressed key issues: (1) Why vehicle electrification matters, (2) vehicle technologies, (3) infrastructure, and (4) policy options. Prepared and contributed papers informed panel discussions, and a rapporteurs' report summarizing those discussions follows. All documents are available at http://web.mit.edu/mitei/.

Symposium participants came from different backgrounds and expressed a wide range of views. Here we summarize for policy makers the key points that we drew from the lively discussions. The figures and table we have included in this summary are explained in greater detail in the subsequent sections of this report. **The summary reflects our own observations and conclusions and is not offered as a consensus view.**

- **Why electrification matters.** Currently, petroleum almost exclusively fuels the United States (US) transportation system, creating two major challenges:

    1. The transportation sector represents a significant fraction of total greenhouse gas (GHG) emissions both globally and in the US — light-duty vehicles (LDVs) are responsible for 17.5% of carbon dioxide (CO_2) emissions in the US. Absent a shift from internal combustion engine (ICE) vehicles, there will be a continuing increase in CO_2 emissions from the transportation sector driven largely by the growth in the large, rapidly growing emerging economies such as China and India. Electrification will reduce emissions, with the scale determined by the carbon intensity of the power sector.

    2. Electrification will reduce oil dependence, providing foreign policy benefits and the potential to reduce real oil prices and oil price volatility.

- **Vehicle technologies.** Alternative fuels, such as biofuels and electrification, are the two broad technology alternatives to petroleum-fueled ICE vehicles. Broadly, there are three different electric vehicle (EV) possibilities:

    1. **Hybrid Electric Vehicles** (HEVs) have both an ICE and an electric motor for propulsion, which can be configured in either series or parallel configuration. The battery can be recharged by conversion of braking energy. HEVs are conventionally fueled.

    2. **Plug-in Hybrid Electric Vehicles** (PHEVs) are HEVs in which the battery is rechargeable by external power sources.

    3. **Battery Electric Vehicles** (BEVs) have only electric propulsion and a rechargeable battery pack.

We shall refer to PHEVs and BEVs together as EVs.

Comparison of the environmental impact, cost, and oil use of these alternative technologies requires a "well-to-wheels" systems analysis with consistent assumptions. Nevertheless, some general expectations provide a frame of reference for the discussion. For vehicles of comparable size and range and the same driving pattern, oil use is progressively less, and costs progressively more, in going from ICEs to HEVs to PHEVs to BEVs. The cost progression can be put in context by recognizing that a PHEV battery is likely to have a capacity of about 10 kilowatt-hours (kWh), while a comparable BEV with a 300-mile range might have a battery capacity in the 70–80 kWh range. The anticipated vehicle battery costs in this decade are expected to be $400/kWh or higher, so the total battery pack cost is very high.

The analogous progression for CO_2 emissions is less clear. All three options are likely to lead to emissions reductions relative to ICE vehicles, but the amount will depend critically on the carbon intensity of the electricity supply. With the current fuel mix of the US power sector (about half coal, about 30% "carbon-free"), CO_2 emissions for HEVs and EVs are similar. The following chart taken from a joint Electric Power Research Institute/Natural Resources Defense Council (EPRI – NRDC) report *Environmental assessment of plug-in hybrids* illustrates quantitatively the strong dependence on the GHG emission characteristics of the source of electricity.[1]

Figure 1 – 12,000 Mile/Yr PHEV 20 GHG Emissions by Fuel/Technology

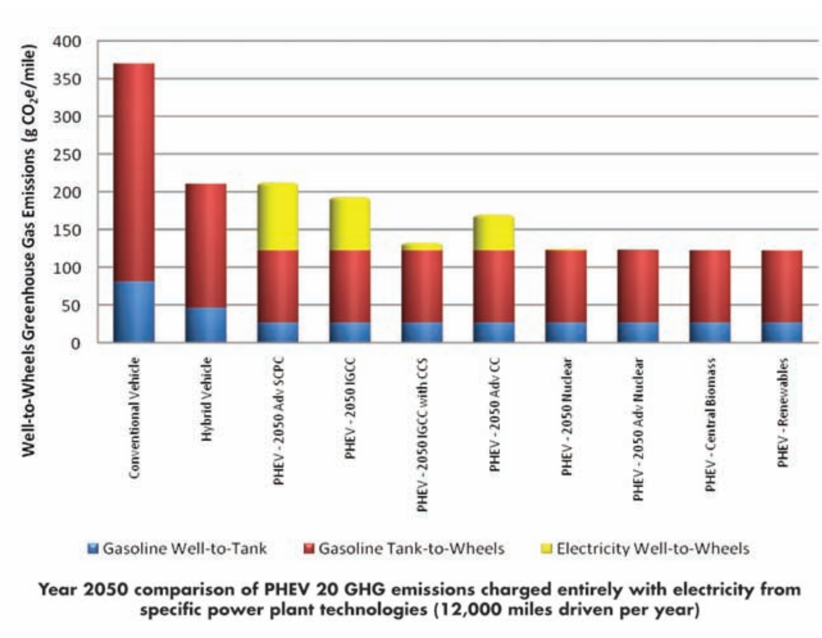
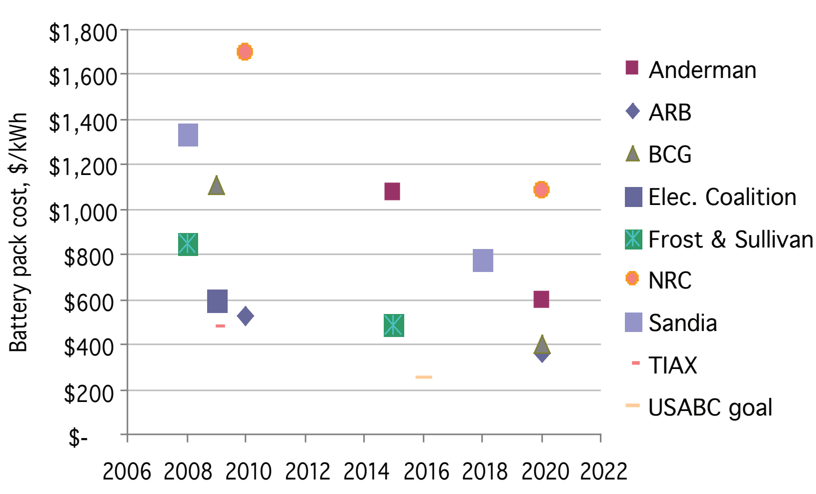


Figure 2 – Cost Estimates of EV Battery Packs



The wide spread of opinion about the mid-term prospects for improved technical performance and cost of EV battery systems based on advanced lithium-ion (Li-ion) or other battery concepts, as shown in the chart from the Sloan Automotive Lab[2], underlines the uncertainty in price/performance of EV battery systems. Some industry participants stated that battery costs are already lower than the Natural Resource Council (NRC) projection for 2020, but this depends on unstated assumptions underlying the different estimates in the chart. A rough rule of thumb is that battery costs must reach about $300 per kWe-h in order to compete with spark ignition, ICE LDVs fueled with $3.50 per gallon gasoline. However, it is important to bear in mind that conventional ICE technology is projected to improve over time with regard to fuel economy and cost. There are also other important battery metrics besides cost: safety, reliability, high energy density, charging time, and buffer levels. It is worth noting that there has been considerable support for battery research and development (R&D) by industry and government both in the US and elsewhere for many years without the kind of major advance that would make EVs economically competitive.

Manufacturing is key to achieving a commercially successful EV battery pack. Low cost is only achieved in large-volume, highly automated factories. This raises two issues. Successful development of EVs requires attention to both R&D and manufacturing of battery systems. Understanding possible economies of scale in manufacturing is an important aspect of battery technology development since manufacturing cost is decisive in the ultimate economics of EVs. Second, battery manufacturing will not necessarily occur in the country that creates the battery technology. This is an especially vexing political question in the US where it is widely believed, perhaps correctly, that high-technology manufacturing of products such as batteries is taking place abroad, especially Asia, despite low labor content. Both issues have implications for the government role in supporting EV development, discussed below.

A strong research program, emphasizing both component technologies and integrative systems analysis, should also be devoted to thinking "out of the ICE-box." That is, EVs — especially BEVs — with powerful electric platforms can be redesigned dramatically with respect to traditional ICE vehicles in ways that offer new urban transportation paradigms integrated with sophisiticated systems of sensors, controls, distributed decision making, real-time modeling and simulation, and IT. Such system approaches are especially important in the context of urbanization trends in developing economies and ideally should influence infrastructure development before "lock-in" of current patterns of urban design. The implications go well beyond the transportation system itself; for example, large-scale deployment of a hierarchy of personal and public urban electric transportation devices can sufficiently influence the environment (e.g., pollution, noise) to allow less energy-intensive building and community design.

- **Infrastructure and consumer acceptance.** All participants agreed that successful penetration of EVs into the transportation market requires consumer acceptance and infrastructure change as well as achieving competitive cost. Important insight into consumer acceptance will come from the market reaction to EVs that are now or soon to be introduced: the PHEV Chevy Volt, the BEV Nissan LEAF, and the BEV Tesla roadster. Consumer reaction to cost, charging time, and range will help point the way forward.

Successful EV market penetration also requires adaption by the electricity system in three ways: (1) assuring there is adequate generation capacity to meet new demand for transportation and understanding the carbon emission characteristics of the incremental generation capacity, (2) enabling the transmission and distribution system to adjust to changes in demand from the transportation system, e.g., by charging EVs using off-peak electricity generation, and (3) developing and deploying an accessible charging infrastructure.

Deploying a charging infrastructure and associated electric vehicle supply equipment (EVSE) is perhaps the most important consideration because of the large number of issues that need to be addressed: the distribution, extent, and standardization of charging stations, setting limits for charging time and access rules, as well as regulatory procedures and policies for commercial firms in the distribution market. Evidently, deciding who pays for the charging infrastructure — the public, utilities, or EV users — and regulating the price for charging vehicles at residences or central stations is key. The role of various jurisdictions — municipalities, state public utility commissions, and the federal government — needs to be defined as well as how state department of motor vehicles (DMVs) will inspect EVs.

As far as who pays, an analogy could be drawn with the Highway Trust Fund, wherein users pay according to fuel use. However, use of EVs, like other vehicle and fuel technology alternatives to petroleum-fueled ICE vehicles, has external benefits such as reducing oil consumption and environmental advantages. These external benefits need to be considered in comparing the social, as opposed to market, benefits of vehicle technology alternatives. There are a variety of measures that the government can implement to internalize external costs and benefits.

These issues will not be resolved quickly. The Department of Energy (DoE) is supporting some activities that bear on these questions, and states are undertaking activities that could yield additional insights if the data is disseminated and analyzed properly. The message here is that the pace of investment and deployment depends on establishing a clear policy and regulatory framework for EVs. Sophisticated simulation and systems dynamics tools can be an important guide to an implementation strategy (technology, policy, regulation, economics) that avoids a "bridge to nowhere." A random approach to experiments could ultimately delay implementation of a robust and reliable infrastructure.

- Policy options. Participants generally agreed that electrification of the LDV transportation sector was desirable because of the potential for CO_2 emissions reduction, lessened oil dependence, and perhaps even lower cost. However, while vehicle electrification was viewed as a desirable objective, there was much greater difference over the policy instruments that should be invoked. Technology advocates generally favor rapid, direct intervention to overcome the technical, cost, infrastructure, and consumer acceptance barriers. Technology agnostics avoid picking technology winners and prefer policies that internalize external cost and establish a level playing field among technologies.

Accordingly, there was wider agreement on measures intended to spur vehicle electrification enabling technology development and demonstration than on measures intended to subsidize early deployment of EVs.

Despite these differences, there are three policy measures that received general support from participants:

1. Establish a comprehensive carbon emission policy that influences the future generation mix so that the environmental benefit of switching from petroleum fuel versus electricity-fueled LDVs is set. The prospect for such a policy at the national level is remote. More likely, is a hodge-podge of state and federal regulation and targeted subsidies for favored technologies.

2. Continue and expand R&D on key vehicle electrification technologies such as batteries, smart charging, lightweight materials, and selective manufacturing technology. The Advanced Research Projects Agency-Energy (ARPA-E) program, although not proven, is an innovative way to pursue technical advance in these areas.

3. Increase emphasis on setting an enabling regulatory framework for EVs and measured demonstration of EV charging and pricing systems.

While there were differences over desirable government measures to encourage deployment by subsidies or regulatory mandates, there was widespread agreement that the vehicle electrification technology option would be much advantaged by coherent, as opposed to a patchwork or regulatory, measures with, in some cases, contradictory purposes. Congress has endorsed numerous subsidies for vehicle electrification beginning with the Energy Policy Act of 2005 (EPAct), continuing in the Energy Independence and Security Act of 2007 (EISA) and in the Emergency Economic Stabilization Act of 2008 (EESA), and culminating in the American Recovery and Reinvestment Act of 2009 (ARRA).[3] Through tax credits for the purchase of PHEVs and BEVs and the allocation of funds for the development of battery manufacturing facilities, the federal government has clearly signaled that it, as a matter of policy, favors electrification of the nation's transportation system. Today, consumers who purchase EVs or PHEVs with a minimum five kWh battery capacity are eligible for a $2,500 tax credit and an extra $417 for each additional kWh of battery capacity, with a maximum credit of $7,500. Individual states, led by California, have regulatory requirements that are intended to speed the penetration of "zero emission" EVs.[4]

The following table summarizes significant programs that have been put into place to encourage vehicle electrification. It vividly illustrates the cost of launching (expensive) programs that target a specific technology from more than one direction. ARRA funding supports both deployment subsidies for batteries or electric cars based on today's technology and R&D, through ARPA-E, based on the premise that current battery technology is inadequate and that future advances are possible. Tax credits presumably are based on the expectation that competitive cost will be realized with economy of scale. Not included in the chart are efforts to use federal procurement to encourage EVs.

	Program	**Legislation**	**Description**	**Cost**
Batteries, Infrastructure and Manufacturing Assistance	Advanced Vehicle Technology Program	American Recovery and Reinvestment Act	Provides direct investment for battery and infrastructure manufacturing deployment — $2.5 billion of which went to battery and component manufacturing plants	$5 billion
	Advanced Technology Vehicle Manufacturing Loan Program	Energy Independence and Security Act 2007	Direct loans to Nissan, Tesla, and Fisker for EV facilities in Delaware, Tennessee, and California. Manufacturers are eligible for direct loans of up to 30% of the cost to reequip, expand, or establish manufacturing facilities	$2.6 billion
	Battery Research and Development Grants from ARPA-E	American Recovery and Reinvestment Act	Direct grants for high-risk/high-reward research on next-generation batteries, specifically ultra-capacitors and metal-air batteries	$80 million
EV Deployment	Plug-In Hybrid Tax Credit	Energy Policy Act of 2005, adjusted with the Energy Independence and Security Act of 2007, Emergency Economic Stabilization Act of 2008, and American Recovery and Reinvestment Act of 2009	For batteries of at least 4 kWh in capacity, this program offers a $2,500 income-tax credit with an additional $417 for each added kWh of capacity, with a maximum credit of $7,500 for up to 200,000 vehicles	$1.5 billion
	Vehicle Electrification Initiative	American Recovery and Reinvestment Act	Provides grants to 11 localities for deployment and integration, includes the cost of vehicles, infrastructure, and workforce education programs	$400 million

Several participants urged sustained federal subsidies in order to maintain this momentum including, at one extreme, a suggestion that the government offer instant payback between ICE and EV cost for those who buy EVs. Others were concerned that the grab bag of policies and their lack of analytical underpinnings created significant potential for unintended consequences, major system gaps, and wasteful spending.

The bottom line for legislatures and state and federal government officials is to suggest a focus on: (1) crafting a coordinated approach to vehicle electrification, (2) continuing R&D especially for battery systems and grid integration, and (3) defining the regulatory framework for EV community operation. For investors and industry managers the message is that the LDV electrification market is not likely to expand greatly over the next decade, although the long term potential is very high.

John Deutch
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CONTENTS

Bill Mitchell

Photo: Webb Chappel

Former dean of MIT's School of Architecture and Planning
MITEI Steering Committee Member
1944 – 2010

William J. Mitchell, the former dean of MIT's School of Architecture and Planning and member of the steering committee for the Electrification of the Transportation System symposium, passed away on June 11 after a long battle with cancer.

Considered one of the world's leading urban theorists, Mitchell pioneered urban designs for networked, "smart" cities and helped to oversee an ambitious building program that transformed MIT's physical campus.

Serving on our faculty advisory committees, MITEI appreciated his advice and counsel on energy issues.

Through the work of his Smart Cities research group at the MIT Media Lab, he pioneered new approaches to integrating design and technology to make cities more responsive to their citizens and more efficient in their use of resources. He likened tomorrow's cities to living organisms or very-large-scale robots, with nervous systems that enable them to sense changes in the needs of their inhabitants and external conditions, and respond to these needs. A major portion of this new urban infrastructure focused on revamping urban transportation as we know it, and included the development of the CityCar, a light-weight, electric, shared vehicle that folds and stacks like supermarket shopping carts at convenient locations and has all essential mechanical systems housed in the car's wheels. Other Smart City innovations include the folding electric RoboScooter, and GreenWheel, which turns an ordinary bicycle into an electric-assisted one.

Mitchell, who was the Alexander W. Dreyfoos, Jr. (1954) Professor of Architecture and Professor of Media Arts and Science, joined MIT in 1992 and over the next 18 years contributed handsomely to the Institute's intellectual life and campus spirit. As dean of architecture and planning, he championed the importance of the visual arts to MIT and concentrated on infusing new energy and visibility into the school by recruiting a number of innovative young faculty members. As a professor in the MIT Media Lab, Mitchell explored the new forms and functions of cities in the digital era, and suggested design and planning directions for the future. He was particularly interested in the relationship between real space, virtual space and human communities.

His legacy is not only in his teaching, vision, and books, but also the transformation of MIT's physical campus and his role in it. It was not uncommon to see him leading community members and campus visitors on tours of the various construction sites. While each building was clearly unique, Mitchell wanted them all to be seen as part of a coherent landscape fabric; accordingly, he pushed for new "connective tissue" around campus — pedestrian routes, landscaping and commons facilities, for instance — to ensure that the whole be greater than the sum of its parts. "The fundamental idea is to weave everything together in a vibrant, residential community," Mitchell said in a 2001 campus talk.

His vision is seen every day in the transformation of the MIT campus.

MIT News Room with additional reporting by Scott Campbell and Ellen Hoffman.

The MIT Energy Initiative's Symposium on Electrification of the Transportation System

FINDINGS IN BRIEF

FROM THE RAPPORTEURS' REPORT ON THE SYMPOSIUM

The proceedings of the MITEI Symposium on the Electrification of the Transportation System are summarized in this report. The report reflects the major points of discussion, and the general findings and recommendations of the participants at the event. It is important to note that this is a report on the proceedings and papers that informed those proceedings; it is not a study. The report represents a range of views from those at the symposium and, where possible, includes consensus or general recommendations from the presenters and participants; *it is in no way intended to represent the views of all the participants, the individual participants, or of the rapporteurs.*

Symposium Structure and Framing of the Issues

The symposium's 68 participants, all experts in the subject matter, helped to frame the issues, opportunities, and challenges associated with vehicle electrification. The findings identify a range of possible "next steps" for the consideration of policy makers and other interested individuals and entities.

Participants engaged in moderated discussions after reading background materials and commissioned white papers provided to them in advance of the event. Discussions revolved around four commissioned white papers, each with an affiliated panel comprised of the author and selected discussants. The authors highlighted key points from their white papers, and selected discussants offered brief responses to the points made by the authors. Symposium participants then engaged in wide-ranging discussions framed by the topics of the white papers, which included:

- Why Electrification Matters
- Vehicle Technologies
- Vehicle Infrastructure
- EV Policy

In addition to the commissioned papers, a number of participants voluntarily supplied various papers and slides to all participants in advance of the April 8th event to further inform and focus the discussion. Data, points of view, and information from these papers are integrated into the text of this report and are available at the MITEI Web site http://mit.edu/mitei. The Honorable David McCurdy, president of the Alliance of Automobile Manufacturers, MIT Institute Professor John Deutch, and MITEI Director Ernest Moniz provided summary remarks at the symposium and led a concluding discussion. A summary of the issues and findings of the symposium follows.

Panel One: Why Electrification Matters

Issues Summary: The almost exclusive reliance of the US transportation system on oil diminishes US foreign policy options, exposes consumers to price volatility, and transfers significant wealth to oil-producing nations.

Further, global energy demand is projected to increase 50% by 2030, with transportation representing a large fraction of this growth, mostly in developing countries, particularly in China and India. The Energy Information Administration (EIA) projects energy demand within Organisation for Economic Co-operation and Development (OECD) countries to rise 0.2% annually compared to 1.9% in non-OECD countries.

Electrification of passenger vehicles is viewed by many as a means to a policy end that seeks to reduce US oil dependence, operate vehicles more efficiently, and reduce carbon emissions. The degree to which EVs help to achieve these policy goals varies depending on market penetration and the level of decarbonization of the US power generation system.

Currently, ICEs provide the propulsion for almost all US LDVs. Beyond pure ICE vehicles, the following options are central to this discussion:

- HEVs have both an ICE and an electric motor for propulsion, which can be configured in either series or parallel configuration. The battery can be recharged by conversion of braking energy. The HEV is conventionally fueled.
- PHEVs are HEVs in which the battery is rechargeable by external power sources;
- BEVs have only electric propulsion and a rechargeable battery.
- EVs, for the purposes of this document, refers to PHEVs and BEVs, both vehicle types that use external power sources.

EVs compete not only with higher-efficiency ICEs, but potentially with fuel alternatives such as biofuels, natural gas, or hydrogen — all of which would help reduce oil dependence and, potentially, carbon emissions.

There is growing market penetration of HEVs. HEVs are generally economically viable without subsidies and have similar GHG reduction potential compared to EVs “fueled” with the current US electricity mix. As the carbon intensity of the electricity sector is reduced, however, there will be corresponding GHG reductions from EVs which will exceed those of HEVs.

Vehicle electrification faces significant challenges. Currently, battery costs price EVs out of the market without government support. Similarly, significant public investment is necessary for vehicle charging infrastructure. Finally, range anxiety and concerns over battery durability threaten consumer acceptance.

Panel One Findings: Why Electrification Matters

Finding: EVs have the potential to reduce US oil dependence. Analysis indicates that oil dependence, price volatility, and the setting of global oil prices by cartels have cost the US economy $5.5 trillion since 1970.

Finding: There are CO_2 emissions reduction benefits associated with electric vehicles. Along with energy security, these benefits are the primary driver for policies to promote the electrification of the US transportation system. The extent of emissions reductions will be determined by the electricity fuel portfolio, though wells-to-wheels analyses suggest that under the current electricity fuel mix, PHEVs will reduce GHG emissions compared to conventional vehicles.

- Conventional hybrids reduce CO_2 emissions by 33% relative to ICEs.
- This compares to a 66% reduction in CO_2 emissions for PHEVs fueled by carbon-free electricity, including nuclear, biomass, and other renewable generation.
- While PHEVs fueled with coal generation (without carbon capture and sequestration (CCS)) have lower CO_2 emissions than those from an ICE, they have higher CO_2 emissions than conventional hybrids.
- PHEVs fueled with combined cycle gas generation can reduce emissions by as much as 50% and have lower emissions than ICEs or conventional hybrids.

Finding: GHG emissions from the transportation sector will be dominated by growth of the transportation sector in the developing world.

Finding: EVs can help address security, climate, and economic issues associated with oil consumption, but even under the most aggressive EV deployment scenarios, the LDV fleet will continue to be dependent upon oil and the ICE for years to come. HEV sales account for 3% of total sales after 10 years on the market. Increasing the EV penetration rate substantially will require major battery cost reductions and significant build-out of vehicle charging infrastructures.

Panel Two: Vehicle Technologies

Issues Summary: A recurring theme of the symposium was that, for EVs to successfully penetrate US markets, consumer acceptance is essential. Without this, the answer to the question “Who killed the electric car?” will likely not involve a sinister conspiracy but will instead simply be “the American consumer.”

The vehicle technologies panel was no exception in stressing the importance of consumer acceptance. There was general agreement that a widely successful EV would not necessarily be the most technologically advanced option, such as the Tesla, but rather one that was affordable, reliable, and practical from the perspective of the average consumer.

Such an EV would need to be able to recharge conveniently, have technologies that allay “range anxiety,” and, perhaps most importantly, be cost competitive with the traditional ICE configuration over the life span of the vehicle.

These features would specifically require further advances in battery technology. Some argued that this would require a shift to new battery chemistries, while others argued that continued incremental technology improvements in Li-ion batteries would be sufficient.

Panel Two Findings: Vehicle Technologies

Finding: EVs are in the nascent stages of market penetration. Successful marketing of EVs will require careful attention to issues of total cost and payback periods, recharge times, and range anxiety.

Finding: The sales of the upcoming Chevrolet Volt, a PHEV, and the Nissan LEAF, a BEV, will help gauge consumer interest in EVs.

Finding: Battery prices and technologies are improving but may not yet be at the stage for wide-scale market penetration without subsidies. Studies from battery manufacturers, analysts, and academics are inconsistent about battery prices in both the short and long term.

Finding: Price per kWh is not the only factor in a "successful" EV battery. Other important factors include battery reliability, life span, and safety — all of which will feed back into consumer acceptance.

Panel Three: Vehicle Infrastructure

Issues Summary: The charging infrastructure will play a key role in consumer acceptance of EVs, especially those with a high degree of electrification (DOE). Although technical standards are currently in place to govern the physical EV charging interface, the standards for EV-to-grid communication are still undergoing revision. Utilities are interested in supporting EVSE installations but disagree over how this should be managed. Private, in-home EVSE may require wiring upgrades, which should be taken into the overall cost of an EV.

In order to avoid stressing the grid, EVs will need to charge intelligently, using off-peak electricity, largely at night. There are a variety of options for intelligent charging, many of which will require some form of communication between the grid and the EV. The deployment of this technology will depend on collaboration with utilities, EV owners and manufacturers, and other stakeholders. Current standards-setting processes will play an important role in the development of this system.

The degree to which government incentives are needed to finance EVSE development is an unresolved issue that will require thorough vetting by policy makers. Regardless, municipalities will need to ensure access to public charging by keeping it safe, reliable, and fair.

Panel Three Findings: Vehicle Infrastructure

Finding: The role of EV infrastructure and policies to support its development need considerable analysis, planning, clarification, and innovation in order to enable significant market penetration of EVs. Uniform definitions, such as smart charging, should be developed and established by requisite policy and standards-setting bodies.

Finding: Because the DOE of EVs is still unclear, it is difficult to determine how much or what type of infrastructure is needed to support EVs. There is agreement that the lack of public infrastructure will impede EV market penetration but disagreement on timing and degree of public support for its development.

Finding: Critical regulatory issues will have to be resolved to enable EVSE installation, both in homes and for public use. State Public Utility Commissions (PUCs) will have to determine if and how to regulate public EVSE.

Finding: Rationalization of regulations will have to occur between government jurisdictions to ensure ease of travel and reliability of the system.

Finding: EV charging will have an impact on the grid. The extent of that impact depends on the existing transmission and distribution infrastructure in areas where EVs are being purchased. It may be necessary to upgrade transformers for residential or commercial customers' installation of EVSE. It is not clear how these upgrades should be paid for and who specifically should bear the cost.

Finding: Assuming significant market penetration of EVs, access to public EVSE must be fair and widely available. Municipalities will need to ensure that rules and regulations are in place regarding charging time, charging order, etc., and will need to penalize those who monopolize charging facilities.

Panel Four: EV Policy

Issues Summary: There was consensus on a central point: the nation lacks a coherent energy policy. The prevailing view was that policy makers have eschewed coherence and cohesion in favor of a collection of a disconnected array of policy choices that represent political but not policy balance. Participants also agreed that erratic approaches to market conditioning — which at times dictate technology choices and at other times, avoid them — were inefficient.

Participants differed on the extent of government intervention acceptable in meeting the environmental and energy security challenges that face the country today. Some advocated for an approach that is technology agnostic in which the government does not pick the winners. Others favored greater government intervention, asserting that certain technologies faced greater social, cultural, and economic hurdles requiring added support to achieve maximum welfare.

Though participants disagreed on the specifics of implementation, there was consensus on the need to establish a carbon price in order to efficiently internalize the environmental and security externalities in the transportation system. The permutations of such a policy that were discussed include an economy-wide carbon cap-and-trade system, a carbon tax, and a gas tax.

Panel Four Findings: EV Policy

Finding: There is a lack of cohesion and clearly defined policy goals in the current assortment of subsidies that comprise US energy policy. A unified energy policy is needed that appropriately defines, analyzes, and sequences public investments and incentives. Electrification of the transportation system would benefit from a more thoughtful approach to what amounts to major nationwide changes.

Finding: Stimulus funding has created significant momentum for technological innovation. One challenge moving forward will be maintaining this momentum when the funding runs out.

Finding: For EV technologies to more rapidly and efficiently scale, there must be a price on carbon in the form of a carbon tax, cap-and-trade system, or gas tax, though the relative effectiveness of these three options was contested.

Finding: A unified policy must achieve three distinct goals: improve the fuel efficiency of new vehicles, reduce the carbon content of fuels, and drive consumer acceptance.

Panel One: Why Electrification Matters

Throughout the symposium, participants stressed two themes:

- Continued dependence on oil results in diminished energy security, a significant trade deficit, and limits to US foreign policy options.

- Carbon emissions continue to threaten the global environment, with the transportation system accounting for a significant portion of projected emissions growth by 2030.

At the same time, reducing GHG emissions from transportation is inherently difficult because of the widely distributed point sources, numbering in the hundreds of millions. Electrification of the transportation system moves emissions upstream, enabling capture of associated emissions from large point sources, limited in number.

Currently, ICEs provide the propulsion for almost all US LDVs. Beyond pure ICE vehicles, the following options are central to this discussion:

- HEVs have both an ICE and an electric motor for propulsion, which can be constructed in either a series or in a parallel configuration. The battery can be recharged by conversion of braking energy. The HEV is conventionally fueled.

- PHEVs are HEVs in which the battery is rechargeable by external power sources.

- BEVs have only electric propulsion and a rechargeable battery.

- EVs, for the purposes of this document, refers to PHEVs and BEVs, both vehicle types that use external power sources.

Global Oil Markets

Over the last five years, global oil demand increased by 11% and is expected to increase another 25% by 2030. Almost all of this growth is expected to occur in developing countries, primarily China and India.[5] Meeting demand while factoring in depletion rates will require an additional 64 million barrels per day (mbpd) by 2030[6] and an investment of $5 trillion.[7]

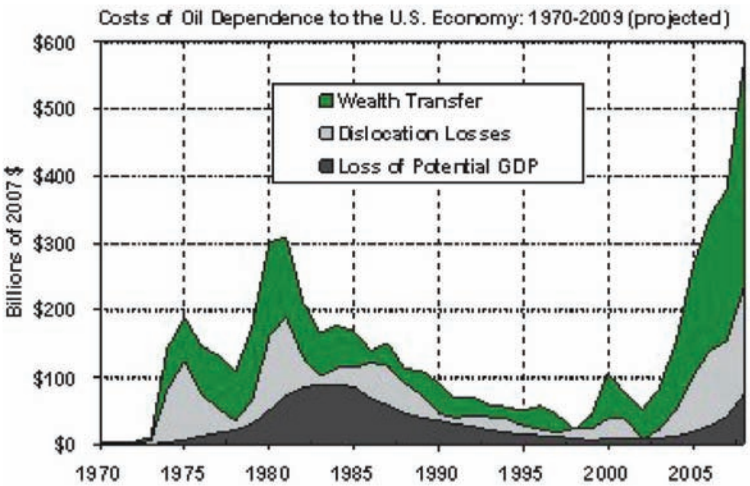
Global oil resources are very concentrated. Demand increases will, in large part, be met by national oil companies (NOCs), which hold between 78% and 90% of the world's proven oil reserves, primarily located in the Middle East.[8] There have been few major oil field discoveries for several decades, suggesting that this concentration of resources is a permanent condition of the oil marketplace.

The ascendancy of the NOCs is problematic, however, because of the role they play in their host governments and social structures. The lack of free and transparent markets and overreliance on oil for federal revenues in many oil-producing nations has resulted in underinvestment in exploration practices and technologies to maximize production.

The US Transportation Market

Since the release of the Model T, the mobility of Americans has been predicated on abundant supplies of relatively inexpensive oil products. The US currently consumes over 20 mbpd, around 23% of global oil demand.[9] The US transportation sector represents around 14 mbpd or 70% of this consumption; of this amount, 8.6 mbpd is for the LDV fleet.[10] The average American household spends approximately $3,600 on 1,100 gallons of gasoline per year.[11] In 2008, US consumers spent $925 billion on oil and refined products.[12]

Figure 3: Economic Impacts of Oil Dependence[15]



The almost-complete dependence of the US transportation system on petroleum-based fuels creates economic vulnerabilities. Indeed, a strong correlation exists between rising oil prices and negative economic growth.[13]

Three specific aspects of the global oil economy can result in a negative impact on the US economy: price volatility, wealth transfer, and the oligopoly market structure.[14] According to Oak Ridge National Labs, oil dependence has cost the US economy $5.5 trillion.[15] Figure 3 charts the total economic loss as a result of price fluctuations, wealth transfer, and market abnormalities. One participant noted that low oil prices can spur economic development.

Between 2003 and 2008, the Organization of the Petroleum Exporting Countries (OPEC) members maintained a spare capacity equal to 3% of daily demand.[16] OPEC reached a 20-year spare-capacity minimum in 2004.[17] Minimal amounts of spare capacity increase the possibility that small market perturbations, e.g., temporary disruptions from storms or refinery shutdowns, can have disproportionate price impacts.[18] The lack of substitutes for oil and gasoline make the demand for the commodity highly inelastic in the short term. These elements, combined with increasing demand in the developing world, promise to perpetuate price volatility. Figure 4 tracks oil prices with geopolitical factors from 1974 to 2008.

The impacts of oil price volatility have a ripple effect throughout the economy and include the misallocation of consumer, business, and governmental resources and a corresponding loss of economic output. Also, increased oil product prices translate into less discretionary consumer spending. Concurrently, other goods that rely on petroleum-fueled supply chains become more expensive in real terms. A $1 per gallon price increase in gasoline results in a 10% reduction in discretionary spending for a US household.[19]

Furthermore, price volatility tends to diminish necessary investment in efficiency and alternatives.[20] The inability to plan for these price fluctuations reduces economic output to a greater extent than a stable high price to which consumers can adjust accordingly.

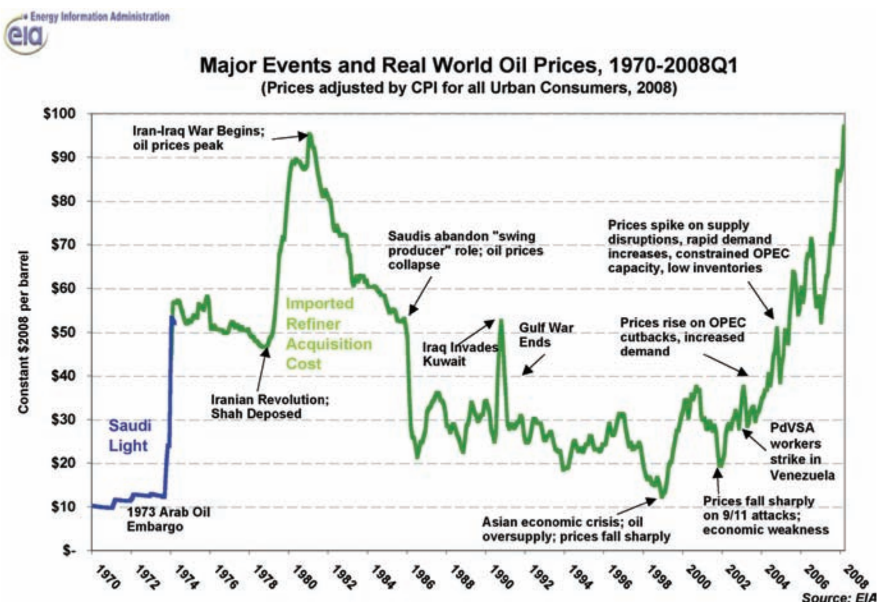
In 2008, the US spent $925 billion on oil and refined products; $388 billion was spent on imported oil and oil products.[21] Oil and oil product imports in 2008 were 57% of the total US trade deficit of $681 billion, representing a significant transfer of wealth out of the US as well as a possible drain on Gross Domestic Product (GDP) as the money spent on goods from abroad may not get reinvested in the US economy.[22] Further, imports are likely to be financed through foreign borrowing, with associated interest payments providing an additional drag on the economy.[23]

The final component of economic loss that derives from oil dependence is the foregone GDP as a result of monopoly power of oil producers. Major oil producers can set their prices above the true market value reducing consumer surplus in the refined products market, and reducing overall welfare throughout the economy as higher prices trickle down.[24]

National Security Considerations

Oil dependence may also threaten national security, largely by limiting US flexibility in pursuing foreign policy objectives, particularly in the Middle East. This is especially true with respect to Iran, the world's fourth largest oil exporter.[25] Any domestic perturbations within Iran could pose a significant harm to global oil markets and correspondingly, the US economy. The oil reliance of US allies places additional limitations on US foreign policy options and strategies. Achieving consensus among allies on Iran sanctions, for example, is complicated by reliance on Iranian oil; the relative proximity of countries to Iran, particularly of countries like Turkey, a North Atlantic Treaty Organization (NATO) ally; and the engagement of allied companies in Iranian production.

Figure 4 – Oil Prices and Geopolitics



Additionally, the unique role of the US in maintaining global security includes securing international oil infrastructure and supply chains.

Environmental Impacts

By 2030, global energy demand is forecast to increase by 50%. The vast majority of this increase in demand will be met with fossil fuels, with a corresponding increase in CO_2 emissions, which are expected to rise 37% over the same time period.[26] However, much of this growth is expected in developing countries, particularly China and India. Indeed, the EIA projects energy demand within the OECD countries to rise 0.2% annually compared to 1.9% in non-OECD countries.[27]

The International Panel on Climate Change (IPCC) warns that an increase in atmospheric CO_2 to 550 parts per million (ppm) would result in a three-degree Celsius increase in average global temperatures.[28] The impacts of this warming, while debated, would likely include sea level rises; loss of habitat; the potential extinction of many species; volatile and extreme weather; increased drought, related fires, and hurricanes; the loss of agricultural output; human displacement; and the concurrent global security risks. Limiting emissions to 550 ppm would require emissions to peak before 2030.[29]

The IPCC recommends that the international community acts to keep GHG emissions below the 450 ppm carbon equivalent. Two-thirds of this reduction would need to occur in non-OECD countries. Meeting this emissions level would require major changes in the transportation sector, including more efficient cars and low-carbon fuels.

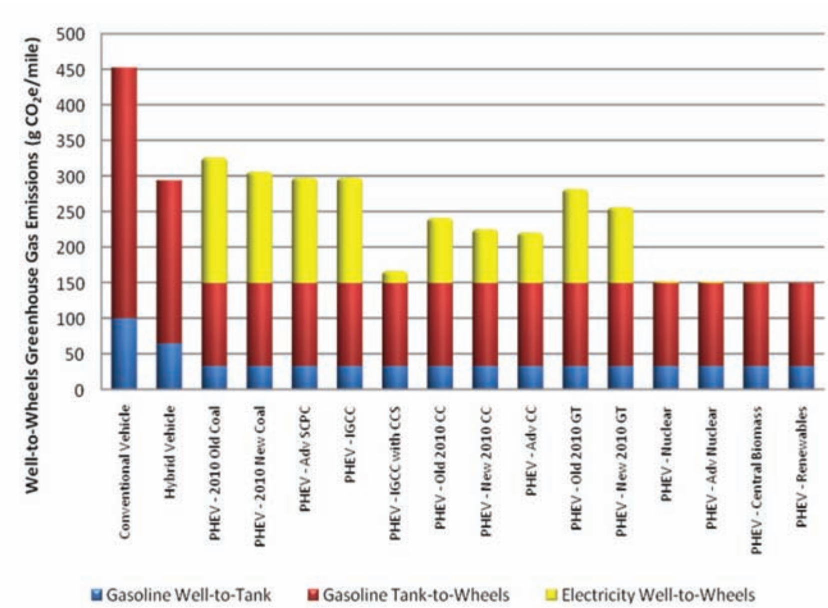
To meet increased oil demand for energy in the global transportation sector in 2030, consumption will increase from today's 85 mbpd to around 105 mbpd. Passenger travel will comprise the largest portion of transportation demand growth, with the majority of this increase occurring in the developing world[30] where relatively immature transportation systems offer significant opportunities for deploying new, lower-emitting transportation technologies and associated infrastructures.

Symposium participants debated whether the 450 ppm scenario recommended by the IPCC was realistic and to what extent this limit should dictate policy. Meeting the 450 ppm scenario would require unprecedented investment in wind and solar energy, CCS technologies, nuclear power, and clean fuels. However, it is unclear even under the most aggressive mitigation investment scenarios whether this scenario is attainable. Participants expressed concern about the impacts of a goal that was viewed as unattainable.

In the US, the LDV fleet is responsible for 17.5% of total carbon emissions.[31] Passenger vehicles emit an average of 400 grams of CO_2 per mile. One participant noted that, in order to meet the global 450 ppm target, emissions from individual vehicles would need to be reduced to 145 grams per mile. EVs can make a major contribution to these emissions reductions. Once EVs have reached significant market penetration, their emissions profile will improve as the electricity sector decarbonizes. Participants asserted the relative facility of improving emissions in power plants rather than individual automobiles.

Comparative CO_2 Emissions

Figure 5 – 12,000 Mile/Yr PHEV 20 GHG Emissions by Fuel/Technology[33]



Year 2010 comparison of PHEV 20 GHG emissions when charged entirely with electricity from specific power plant technologies (12,000 miles driven per year).

Coal currently fuels around 45% of electricity generation in the US. In view of this high level of coal generation, several participants questioned the value of EVs in reducing CO_2 emissions. Well-to-wheels analyses conclude, however, that even with the current US generation fuel mix, EVs would produce less CO_2 than conventional vehicles fueled with petroleum.[32]

Figure 5 shows the well-to-wheels emissions profiles of PHEVs fueled with a range of generation technologies compared to baseline emissions from conventional ICEs and conventional hybrid vehicles. Not surprisingly, CO_2 emissions from PHEVs are lower as power generation technologies are decarbonized.[33]

- Conventional hybrids reduce CO_2 emissions by 33% relative to ICEs.
- This compares to a 66% reduction in CO_2 emissions for PHEVs fueled by carbon-free electricity, including nuclear, biomass, and other renewable generation.
- While PHEVs fueled with coal generation (without CCS) have lower CO_2 emissions than those from an ICE, they all have higher CO_2 emissions than conventional hybrids.
- PHEVs fueled with combined cycle gas generation can reduce emissions by as much as 50% and have lower emissions than ICEs and conventional hybrids.

In addition, EVs have the potential to reduce point-source tailpipe emissions, particularly nitrogen oxide (NO_x) and particulates.[34] This occurs because EV charging at night favors dispatch from larger, more efficient generation units. This could translate into health benefits, reducing associated asthma and other respiratory diseases, especially in urban areas. These benefits, however, could be offset in areas with concentrated coal generation where the higher loads associated with EVs could also increase sulfur oxide (SO_x) emissions.[35]

Vehicle Electrification and the Alternatives

Participants noted that vehicle electrification could promote fuel diversity, given the current mix of fuels for power generation in the US (although, as noted above, the CO_2 impacts of electrification vary fairly dramatically based on the fuel used for power generation).

It was also noted that the security benefits of electrification of transportation follow because electricity is generated almost entirely from domestic fuels while oil is largely imported. The US is currently a net coal exporter and has substantial renewable and natural gas resources. Although the US imports uranium (U), the cost of U represents an insignificant portion of the cost of the power generated from a nuclear plant and there are diverse sources of U in the world.[36]

In addition, electricity prices are generally less volatile than oil prices, because the underlying cost of fuel represents a relatively smaller portion of the retail price of electricity. Participants noted the distinction between retail and wholesale prices. In general, regulators shield consumers from short-term price volatility, the impacts of which are felt upstream of end users.

HEVs

Participants acknowledged that the HEV, which is currently competitive with today's ICEs, is the EV's primary competitor. A participant contended that efficiency improvements for HEVs are largely found in weight reductions and incremental improvements in the drive train, as the ICE component of HEVs is already optimized; this was disputed. Corresponding efficiency gains in EVs add to their cost.

Further, as demonstrated in Figure 5, depending on the generation mix, HEVs can reduce vehicle emissions more than EVs. Similarly, efficiency gains in conventional ICE vehicles are competitors to both EVs and PHEVs. Efficiency gains in ICEs translate into relative increases in payback periods for EVs, potentially reducing their viability. Indeed, some participants argued that efficiency gains for conventional vehicles offer the nearest-term, least-costly mitigation strategy for GHG emissions.[37]

Increasing Domestic Oil Production

Theoretically, increasing domestic oil production would minimize the external costs of oil dependence. DoE forecasts a 1.35 mbpd increase in domestic oil production between 2020 and 2030.[38] Increases in global oil demand, however, are expected to exceed this relatively small US increase in production. The US cannot insulate its markets from global oil markets; this small increase is insufficient to diminish the impacts of global oil price volatility on the US economy.[39]

Biofuels

Biofuels, which could be domestically produced, offer a third potential alternative to fuels for EVs and today's LDV fleet. Participants, however, disagreed about the extent to which biofuels would be able to insulate US consumers from the externalities of oil.

Some participants asserted that, in the recent past, because oil prices are set at the margin, the availability of only nine million gallons of ethanol resulted in a drop in prices of $.35 per gallon of oil and an overall savings to consumers of $20 to $40 billion.

Other participants discounted the capacity of biofuels to enhance energy security. Absent the *total* displacement of oil or a major diminution of its value as a strategic commodity, any significant percentage of oil imports would still tie the US to international oil markets and the associated price volatility. Further, depending on the level of US biofuels consumption and the willingness of global oil producers to shut in capacity, producing nations in OPEC, for example, could simply respond by reducing oil production to levels that correspond to levels of biofuels production in the US. Saudi Arabia has demonstrated its willingness and capacity to shut in production in the past over market share concerns, most notably in the mid 1990s when Venezuela was making major incursions into the US market.

Natural Gas Vehicles

Another alternative to petroleum-fueled vehicles is Natural Gas Vehicles (NGVs). Again, participants disagreed on the potential of this alternative relative to EVs or the existing fleet.

Several participants contended that new technologies to affordably produce vast domestic shale gas resources are "game changers" that could enable large-scale penetration of natural gas-fueled vehicles. Others felt that natural gas was more appropriately used in the power sector, where a significant infrastructure already exists and where gas-generated electricity could help lower CO_2 emissions from EVs relative to coal generation. They argued, in general, that combustion of natural gas emits 30% less CO_2 than oil and 50% less CO_2 than coal to produce the same amount of energy.[40] Combined-cycle natural gas plants can achieve efficiency levels of 60%, yielding a 70% reduction in emissions relative to conventional pulverized coal generation.[41]

While both EVs and NGVs have significant infrastructure requirements, there are major differences in their relative efficiencies. An NGV does not have comparable efficiency gains relative to electrification via natural gas generation. In general, 1,000 cubic feet (cf) of natural gas, converted to electricity, yields 457 miles in an EV. This same 1,000 cf in an NGV would only have a range of around 224 miles.[42]

Hydrogen Vehicles

A fifth alternative is hydrogen vehicles. Today, hydrogen is the most expensive alternative, and by consensus of the participants, the least viable, in spite of significant investment in R&D during the Bush Administration.

Energy density is a major drawback for hydrogen transportation as is manufacturing quantities of hydrogen at a scale sufficient to fuel the automotive fleet.[43] Safety and infrastructure issues also present major barriers to large-scale, near-term questions.[44] Hydrogen vehicles do, however, use electric drive trains and share many components with EVs, and therefore, hydrogen vehicles could potentially succeed EVs, assuming that the cost, storage, manufacturing, safety, and infrastructure issues are resolved.[45]

Challenges of Electrification

There are a number of challenges associated with electrification of the vehicle fleet:

- Significant subsidies such as the current federal tax credit are required to keep EVs from being priced out of the market.
- The charging infrastructure is deficient or nonexistent and requires a major investment on the part of both the government and the private sector.
- Regulatory structures are inadequate or nonexistent and would most likely be required at all levels of government.
- A massive penetration of EVs could strain the grid as currently configured.

These issues are discussed in greater detail in the next two sections.

Participants also expressed concerns about consumer acceptance of EVs, noting that chargers are expensive and batteries take three to four hours to charge; this compares to three to four minutes to fill a gas tank at relatively low cost.

In addition, participants noted that, although consumers drive an average of only 33 miles per day and a typical EV can go 40 miles on a charge (the Nissan LEAF has a battery range of 100 miles), "range anxiety" dampens consumer acceptance. Participants were warned by experts that data focused on averages are not adequate; models of human behavior and technical systems suggest that acceptance will likely depend on being far better than average.

Participants concluded this panel by discussing market projections for EVs. Timescales are extremely important to understanding the potential for market penetration of EVs or any of the alternatives. Achieving an EV market penetration of 1% by 2020 would entail a 30% year-over-year growth rate for 10 years. This growth rate would be greater than the fastest growth rate in the automotive industry to date of 10% year-over-year. Further, a 40% PHEV penetration scenario would only displace 7% of oil consumption. These figures demonstrate the difficulty of fundamentally changing the LDV fleet.

Issues Summary: The almost exclusive reliance of the US transportation system on oil diminishes US foreign policy options, exposes consumers to price volatility, and transfers significant wealth to oil-producing nations.

Further, global energy demand is projected to increase 50% by 2030, with transportation representing a large fraction of this growth, mostly in developing countries, particularly China and India. The EIA projects energy demand within OECD countries to rise 0.2% annually compared to 1.9% in non-OECD countries.

Electrification of passenger vehicles is viewed by many as a means to a policy end that seeks to reduce US oil dependence, operate vehicles more efficiently, and reduce carbon emissions. The degree to which EVs help to achieve these policy goals varies depending on market penetration and the levels of decarbonization of the US power generation system.

Currently, ICEs provide the propulsion for almost all US LDVs. Beyond pure ICE vehicles, the following options are central to this discussion:

- HEVs have both an ICE and an electric motor for propulsion, which can be constructed in a series or parallel configuration. The battery can be recharged by conversion of braking energy. The HEV is conventionally fueled.

- PHEVs are HEVs in which the battery is rechargeable by external power sources.

- BEVs have only electric propulsion and a rechargeable battery.

- EVs, for the purposes of this document, refer to PHEVs and BEVs, both vehicle types that use external power sources.

EVs compete not only with higher-efficiency ICEs, but potentially with fuel alternatives such as biofuels, natural gas, or hydrogen, all of which would help reduce oil dependence and, potentially, carbon emissions.

There is growing market penetration of HEVs. HEVs are generally economically viable without subsidies and have similar GHG reduction potential compared to EVs “fueled” with the current US electricity mix. As the carbon intensity of the electricity sector is reduced, however, there will be corresponding GHG reductions from EVs which will exceed those of HEVs.

Vehicle electrification faces significant challenges. Currently, battery costs price EVs out of the market without government support. Similarly, significant public investment is necessary for vehicle charging infrastructure. Finally, range anxiety and concerns over battery durability threaten consumer acceptance.

Panel One Findings: Why Electrification Matters

Finding: EVs have the potential to reduce US oil dependence. Analysis indicates that oil dependence, price volatility, and the setting of global oil prices by cartels have cost the US economy $5.5 trillion since 1970.

Finding: There are CO_2 emissions reduction benefits associated with EVs. Along with energy security, these benefits are the primary driver for policies to promote the electrification of the US transportation system. The extent of emissions reductions will be determined by the electricity fuel portfolio, though wells-to-wheels analyses suggest that under the current electricity fuel mix, PHEVs will reduce GHG emissions compared to conventional vehicles.

- Conventional hybrids reduce CO_2 emissions by 33% relative to ICEs.
- This compares to a 66% reduction in CO_2 emissions for PHEVs fueled by carbon-free electricity, including nuclear, biomass, and other renewable generation.
- While PHEVs fueled with coal generation (without CCS) have lower CO_2 emissions than those from an ICE, they have higher CO_2 emissions than conventional hybrids.
- PHEVs fueled with combined cycle gas generation can reduce emissions by as much as 50% and have lower emissions than ICEs or conventional hybrids.

Finding: GHG emissions from the transportation sector will be dominated by growth of the transportation sector in the developing world.

Finding: EVs can help address security, climate, and economic issues associated with oil consumption, but even under the most aggressive EV deployment scenarios, the LDV fleet will continue to be dependent upon oil and the ICE for years to come. HEV sales account for 3% of total vehicle sales after 10 years on the market. Increasing the EV penetration rate substantially will require major battery cost reductions and significant build-out of vehicle charging infrastructures.

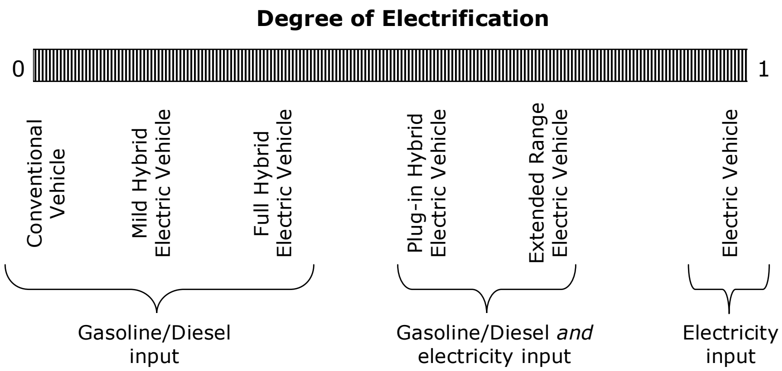
Panel Two: Vehicle Technologies

The term "vehicle technologies" encompasses a wide range of technology options and applications, from vehicle drive train configurations to battery chemistry. There was no consensus among participants on which technologies would ultimately be successful. There was, however, a consensus that consumer concerns about vehicle cost and convenience are more important to the success or failure of the electrification of the transportation system than any particular EV technology or configuration.

Vehicle Types

In discussing EVs, it is important to define the DOE. For an ICE vehicle, the DOE is zero, while an EV has a DOE of one. A range of hybrids falls in the middle, as depicted in Figure 6, each with different performance characteristics, technical requirements, and cost curves.

Figure 6 – DOE for Vehicle Types[46]



The most significant difference between these vehicles is in the drive train, comprising the set of components that produces vehicle propulsion. In a traditional ICE vehicle, the engine is the sole source of propulsion. Adding an electric motor to the drive train enables the use of electricity for propulsion, thereby creating three classes of vehicles: HEVs, PHEVs, and BEVs. In this paper, the term "EV" refers to PHEVs and BEVs.

Both an HEV and a PHEV have an ICE, as well as an electric motor and battery for propulsion. An HEV, such as the Toyota Prius, can recharge its battery by regenerative braking. A PHEV, such as the Chevy Volt, also has regenerative braking and, in addition, can recharge its battery through a direct connection to a power outlet. Battery storage capacity for an EV depends upon the desired DOE and drive train configuration; the battery capacities of major in-production EVs are listed in Table 1. HEVs are gasoline powered only; they cannot plug into a power outlet to charge.

A BEV, such as the Nissan LEAF, is exclusively propelled by an electric motor and battery, which must be recharged by directly connecting it to a power outlet. The Better Place model suggests a BEV for which the battery would be swapped out rather than directly connecting the vehicle to a power outlet. Better Place's model would centralize battery charging at automated swapping stations that the company would build and maintain. The BEV's new battery would already be fully charged, meaning that the owner would not have to wait to charge, only to swap, a process which requires just a few minutes. The depleted battery is left behind at the charging station to recharge and eventually be swapped into a different BEV. The current consensus is that this model works well in small countries, but may not be scalable to the degree required for nationwide deployment in the US.

HEVs and PHEVs have three main drive train configurations: parallel, series, and power split. These are described in Table 1.

Table 1 – Common HEV and PHEV Drive Train Configurations

HEV and PHEV Drive Train Configurations

Parallel: In this configuration, both an ICE and an electric motor can provide propulsion. These hybrids allow for regenerative braking, in which energy from braking can be stored in the battery and later used for electric propulsion. The parallel drive train is generally considered to result in “mild” HEVs, as seen in Figure 6, including some of those produced by Honda. It is most efficient at high, constant speeds, such as on highways.

Series: Although the vehicle has both an ICE and an electric motor, only the motor provides vehicle propulsion. The ICE is used solely as an electricity generator to recharge the battery. As in the parallel configuration, regenerative braking can also be used to recharge the battery. The primary advantage of the series configuration is that the battery can act as a power buffer, allowing the engine to operate at a consistent and efficient speed, instead of having to rev up and down as it would in stop-and-go traffic.

Because the ICE is no longer being used for full-time propulsion, its size may be reduced, although the size of the battery and motor may have to be increased. This makes series EVs more expensive than parallel EVs. Series PHEVs are sometimes referred to as “extended range electric vehicles (EREVs),” because they may initially fully charge their battery from a power outlet and, after exhausting this charge, use the ICE as a generator. The Chevy Volt is an example of this configuration.

Power-split: Sometimes also referred to as “split” or “series/parallel,” this drive train configuration combines the parallel and series configurations as described above. The ICE can provide direct propulsion, as in the parallel configuration, or it can be used to recharge the battery, as in the series configuration. This allows the engine to operate in its most efficient zone during stop-and-go traffic, as in the series configuration. During high-speed travel, the ICE is used for propulsion directly, as in the parallel configuration, thereby avoiding the ICE-to-electricity losses that would have existed under a series configuration.

The series/parallel requires both a large ICE and battery, which makes the vehicle more expensive than either the series or parallel configuration, but allows for efficiency benefits from both the series and parallel configurations. The Toyota Prius is an example of a power-split drive train configuration.

Vehicle Types and Their Trade-offs

Trade-offs fall into the following general categories: weight, range, cost, infrastructure needs, and emissions. Infrastructure and emissions are discussed elsewhere in this report.

Weight

A BEV, for example, would have no mass from an ICE, but would have an increased electric drive train mass, owing to its larger battery, motor, and associated control equipment. EVs with both an ICE and electric motor will have variable masses according to the size of their respective engines, motors, and batteries. A mass/propulsion engineering trade-off must balance the weight of the ICE, battery, and motor against driving performance.

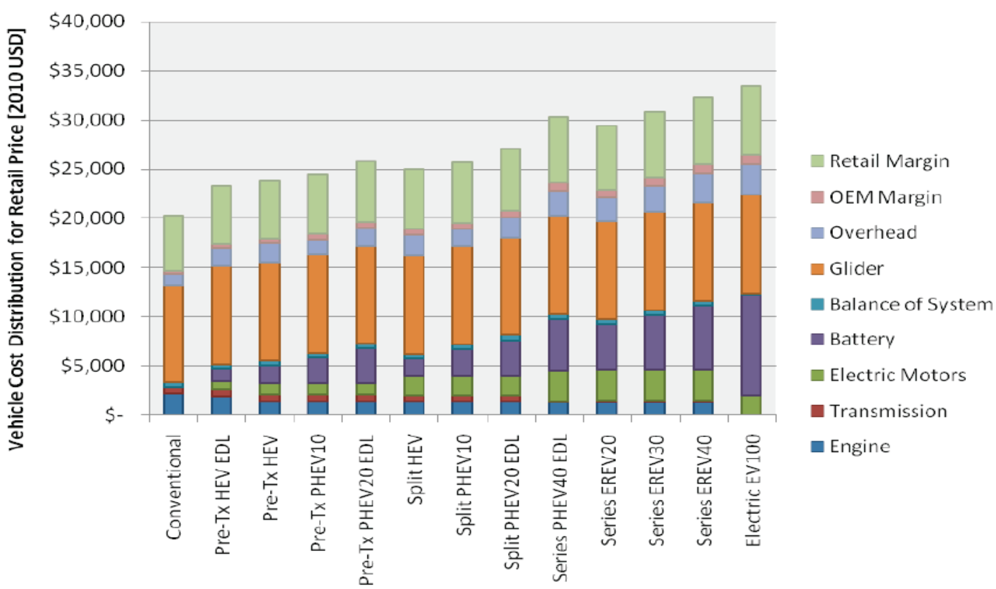
Driving Range

Range — the distance that a vehicle can drive on a single charge compared to a tank of gasoline, or both, depending on its DOE, is a highly useful metric. This distance will vary according to driving styles, which further depends on the type of driving done, i.e., urban vs. rural vs. highway. Stop-and-go driving will decrease the mileage of both an EV and a traditional ICE vehicle; this type of driving will also affect the power-split or series hybrid but to a lesser degree.

Cost as Proxy for Consumer Acceptance

The issue of consumer acceptance was a persistent theme of the symposium. Consumer willingness to purchase an EV along the DOE continuum has not been meaningfully gauged but cost is frequently singled out as a useful indicator. Figure 7 depicts a range of vehicle costs, as a function of DOE, assuming a manufacturing volume of 100,000 cars per year.

Figure 7 – Retail Cost of Vehicles on a Range of DOE at a Volume of 100,000 Vehicles/ Year.[47] Lifetime Costs Including Maintenance and Fuel Not Shown

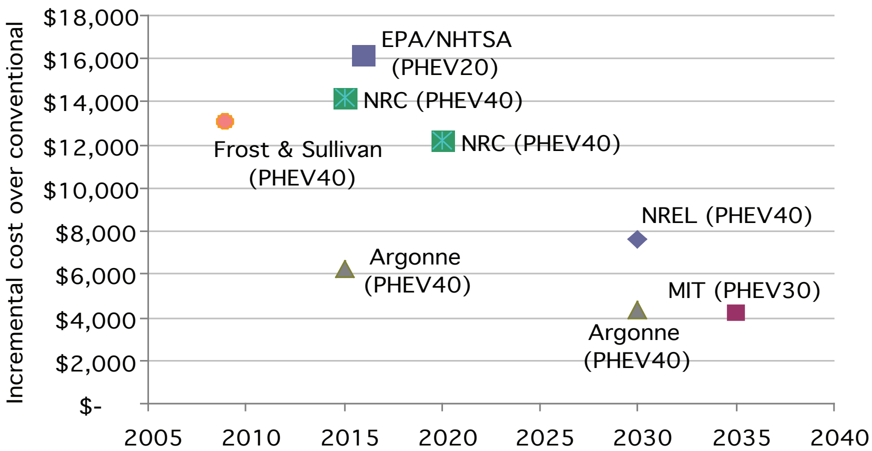


As seen in Figure 7, conventional ICE vehicles remain the least expensive option at about $20,000, while a BEV with a range of 100 all-electric miles costs an additional $14,000. Increasing battery life span may also help make EVs cost effective.[48] Figure 7 illustrates why subsidies are necessary if, as a matter of policy, there is a wish to enable large-scale penetration of EVs in the near term. It also suggests the need for significant cost reductions in EV batteries, as well as the cost chassis and axles of the vehicle (referred to as the "Glider" in Figure 7).

These data prompted some participants to question the economic sense of EVs absent major battery cost reductions and sustained high gasoline prices. Policy mechanisms for achieving sustained high gasoline prices sufficient to offset the additional capital investment required for EVs have been suggested in the past but are highly problematic from a policy and political perspective.[49]

Some participants noted that consumers already purchase expensive luxury ICE vehicles despite the fact that they are based on the same technology as a $20,000 ICE vehicle; an EV, regardless of high lifetime costs, could be branded in ways that make it similarly appealing to high-end consumers (although they still represent a limited market). The costs shown in Figure 8 can, of course, be expected to be lower over time as vehicles and their component parts are produced in greater quantities and as technologies improve.

Figure 8 – Estimates of PHEV Costs Over Traditional ICE Vehicle Costs[50]



There is currently, however, significant uncertainty about technology choices. Because vehicle cost will likely play an important role in consumer acceptance, uncertainty about the future costs of EVs makes it difficult for policy makers to determine whether there needs to be government subsidization of an EV infrastructure. Moreover, it may make it difficult for auto manufacturers to assess the market and plan for investments in new production lines. This uncertainty is highlighted by the findings of several studies that have projected cost differentials between EVs and conventional ICEs; as seen in Figure 8, these vary by thousands of dollars.

Cost Is Not the Only Criterion

Some participants maintained that cost alone is not a good metric to predict future technologies and offered suggestions on other non-propulsion technology advances that could provide greater benefits to consumers. Reduction in vehicle mass, for example, would boost overall efficiency regardless of propulsion technology. This could be done through advances in materials or even onboard computerized collision avoidance.

There was disagreement over the future prices of propulsion technologies across the full DOE scale. Several participants argued that ICE technologies will likely improve at the most rapid rate compared to all EVs, regardless of the DOE. Others maintained that the downward trajectory of the total costs of battery and battery propulsion technologies was steep and that prices were dropping rapidly, sufficient to place EVs on a cost-competitive basis with the traditional ICE vehicle in the not-too-distant future. Table 2 summarizes information about major EVs about to reach or already on the market.

Table 2 – General Information for Upcoming PHEVs and BEVs[51, 52, 53, 54]

Vehicle Name	Anticipated Sale Date	Cost (USD)	Battery Capacity (kWh)	Range
Chevrolet Volt (EREV)	Arriving at the end of 2010	MSRP $41,000 (a federal tax credit of up to $7,500 is currently available)	16 (of which 8 kWh is usable)	40 miles electric, 300 miles on ICE
Nissan LEAF (BEV)	Limited release starting December 2010	MSRP $33,720 (a federal tax credit of up to $7,500 is currently available)	24	100 miles pure electric
Tesla Roadster (BEV)	Now	$109,000 (a federal tax credit of up to $7,500 is currently available)	56	245 miles pure electric

There was also concern expressed by several participants about consumer acceptance of the recharge time requirements for EVs. Traditional ICE vehicles only take about five minutes to refuel, while a pure EV can take several hours to recharge, depending on the kind of charger used. A number of participants expressed doubt that drivers would be willing to wait more than a few minutes to recharge.

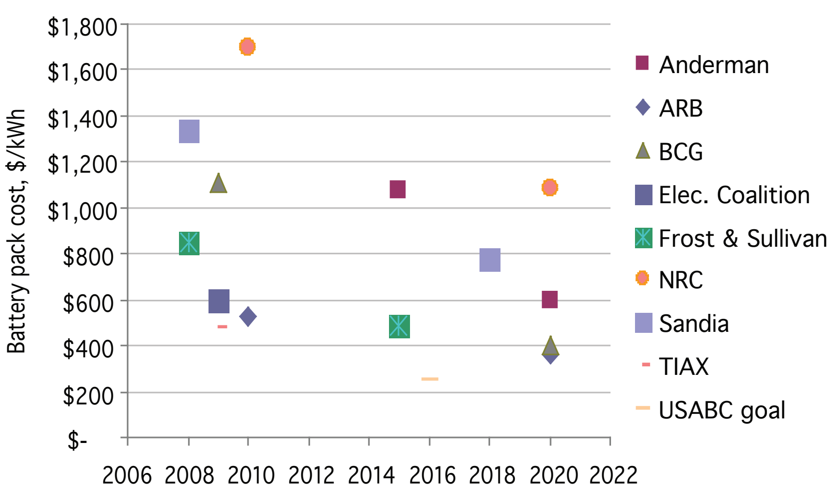
Participants discussed consumer "range anxiety" over the distance limitations of today's EVs. EV proponents pointed out that the range of EVs is adequate for meeting the average distance-traveled needs of the typical driver and that these could be met with an overnight charge from a level 2 charger, which is further discussed in the next section. There is currently little real data or information on consumer acceptance of these limitations, which remain a serious issue that should be examined in much greater detail. Gauging consumer understanding and acceptance of charging times for EVs is a key need going forward.

Battery Technology

Batteries are integral components of EVs and account for a significant portion of the cost differential between EVs and traditional ICE vehicles.[55] There is also a wide range of uncertainty about future battery prices as seen in Figure 9.

Again, the wide variability of future battery costs per kWh adds to the uncertainty of the EV market. Some participants maintained that battery costs are already lower than those identified in the NRC analysis depicted above. Actual cost data from manufacturers are not publicly available, however, largely because of proprietary restrictions.

Figure 9 – Cost Estimates of EV Battery Packs[56]



It is important to note the advances in batteries to date. EVs have, in the recent past, shifted from using nickel metal hydride (NiMH) to relying almost entirely on Li-ion cells, which, while more expensive, have better energy storage characteristics. Absent a disruptive technology breakthrough in battery chemistry, Li-ion batteries will likely be the dominant battery technology for the foreseeable future.

Significant cost reductions are anticipated for Li-ion batteries. Li-ion battery packs for home use are currently below $250/kWh, and it is expected that batteries for automotive use will follow a similar trajectory, with $500/kWh attainable by 2015, with even greater declines thereafter. According to a recent study, PHEVs become competitive with conventional vehicles when battery costs reach $300/kWh, based on a 2008 average gas price of $3.21/gallon.[57]

Cost per kWh is only one dimension of battery requirements. Other battery metrics are outlined in Table 3.

Table 3 – Battery Metrics

Battery Metrics Beyond $/kWh

Safety: Safety concerns center on the effects of a collision or other types of accidents on the chemicals inside the battery. The general consensus is that batteries and their control systems can be designed to ensure safe operation even in an accident.

Reliability: Reliability focuses on consistent performance under similar conditions of use for batteries produced on one or more production lines. This could vary according to manufacturing processes and battery chemistry which could produce identical vehicles that travel variable distances on one charge or have life spans that are shorter or longer than anticipated.

Power density: Power density is the amount of power that a battery can provide per unit volume. Batteries with high power density are useful for automotive applications, where added weight reduces mileage and performance.

Battery buffer levels: Fully charging or discharging a battery can shorten its life span, so a "buffer" is used to prevent the battery charge state from ever approaching a fully charged or discharged state. Buffers are measured as a percentage of the entire battery capacity, and, for automotive applications, typically are set at around 50% of the battery's capacity. Some participants believe that they could reach around 20% over the next five years. Smaller buffers will help bring down the mass, volume, and cost for batteries in automotive applications.

Battery life span: Life span is typically measured in years of expected use, but can also sometimes be discussed as the amount of times a battery can be charged and discharged before it no longer holds a charge sufficient for its application. This is known as a "charge cycle," and batteries exist that have the capacity for 300,000 charge cycles. Fully charging and discharging the battery is known as a "deep cycle," and is generally avoided for the reasons mentioned above. An EV battery with a 10-year life span is projected to require over 4,000 deep cycle charges; some audience members expressed confidence that such batteries could be produced at low prices, given sufficient manufacturing scales. Nissan recently announced that the LEAF will have an eight-year/100,000-mile warranty; Chevrolet had previously announced the same coverage for its Volt.[58, 59]

Many participants expressed confidence that the metrics would continue to improve as a result of increased manufacturing volume, the impacts of federal subsidies, and data from use in the field. The introduction of the Nissan LEAF and the Chevrolet Volt into the marketplace will provide meaningful, real-world data and experience on the performance and market viability of Li-ion batteries and overall consumer acceptance of EVs.

While Li-ion batteries dominated the discussion, some argued that this assumption in effect represented a premature down-select and urged more imagination on the part of the innovation community. They cautioned that investment in alternatives should not be staved and that we should also continue to focus on breakthroughs that might be derived from innovations in battery chemistry.

Issues Summary: A recurring theme of the symposium was that, for EVs to successfully penetrate US markets, consumer acceptance is essential. Without it, the answer to the question "Who killed the electric car?" will likely not involve a sinister conspiracy but will simply be "the American consumer."

The vehicle technologies panel was no exception in stressing the importance of consumer acceptance. There was general agreement that a widely successful EV would not necessarily be the most technologically advanced, such as the Tesla, but rather one that was affordable, reliable, and practical from the perspective of the average consumer.

Such an EV would need to be able to recharge conveniently, have technologies that allay "range anxiety," and, perhaps most importantly, be cost competitive with the traditional ICE configuration over the life span of the vehicle.

These features would specifically require further advances in battery technology. Some argued that this would require a shift to new battery chemistries, while others argued that continued incremental technology improvements in Li-ion batteries would be sufficient.

Panel Two Findings: Vehicle Technologies

Finding: EVs are in the nascent stages of market penetration. Successful marketing of EVs will require careful attention to issues of total cost and payback periods, recharge times, and range anxiety.

Finding: The sales of the upcoming Chevrolet Volt, a PHEV, and the Nissan LEAF, a BEV, will help gauge consumer interest in EVs.

Finding: Battery prices and technologies are improving but may not yet be at the stage for wide-scale market penetration without subsidies. Studies from battery manufacturers, analysts, and academics are inconsistent about battery prices in both the short and long term.

Finding: Price per kWh is not the only factor in a "successful" EV battery. Other important factors include battery reliability, life span, and safety, all of which will feed back into consumer acceptance.

Panel Three: Vehicle Infrastructure

EV infrastructure — recharging stations and their associated equipment in homes, at businesses, and along roadsides — is at the heart of successful EV market penetration, which will not likely occur without convenient, affordable, and accessible charging infrastructure. Furthermore, with widespread vehicle electrification, EVs will have a significant impact on the electric grid.[60] This means that the EV infrastructure must be accessible, standardized, and intelligent.

Accessibility

EVs must plug into a power outlet to charge. Access is relatively easy for residents of single-family dwellings with electric outlets in garages or other residence-exclusive outlets. Options are more complicated for residents of townhouses or apartments referred to as multi-dwelling units (MDUs). Prius purchases, as proxy for gauging market interest in EVs, are highly concentrated in urban areas,[61] where many people live in MDUs without individual access to the requisite charging outlets.

EV Charging by Residents of MDUs

Successful market penetration of EVs that require plug-in charging in urban areas with high-density MDUs will require the installation of accessible charging stations. These stations are frequently referred to as EVSE. EVSE could be installed in parking lots, garages, on the sides of the streets, and in business areas — consistent with local needs, zoning, and other regulatory requirements. As is common for public infrastructure installations, the question of who should pay the capital costs, including any necessary upgrades to the grid — such as new transformers or wiring — is controversial. Solutions may vary by city or municipality.

It is likely that only a limited number of EVSE installations could be placed in each parking lot or along roadsides to provide charging access; some parking spots would not have EV recharging capabilities. Government entities, most likely municipalities, would need to establish regulations to ensure that EV owners had access to parking spots near EVSE. For example, parking lot owners or managers are already familiar with separated parking schemes, such as those that accommodate compact vehicles. Relevant disability accessibility regulations would also have to be taken into account, as well as the possibility of vandalism, and electric and building codes, which may vary in places prone to flooding,[62] heavy snow, earthquakes, and other natural events or disasters.

More problematic will be the apportionment of the additional costs associated with communal recharging locations. A payment system for EVSE services must be established. Some will say payment should not involve subsidization by non-EV drivers. Proposed solutions suggest the use of a card reader or wireless card reader,[63] which should give non-local residents access to the EVSE as well.

There are also related questions of "charging fairness." How long should an EV be allowed to charge at public EVSE before moving on, so that other drivers have a chance to charge? Should charging at public EVSE be first-come first-served, or should it be scheduled?

Answering these questions will require economic, social, and technical analyses as well as the balancing of interests of a range of stakeholders.

The installation of EVSE has also run into problems with state regulations. Until recently, any seller of electricity in California, which would have included EVSEs, was legally regarded as a utility.[64] Such treatment involves a very high level of regulation that would likely deter EVSE installation, especially by small business owners. A recently proposed California PUC rule holds that electricity sales for the purpose of "vehicle motor fuel" should not be regulated in the same fashion as a utility.[65]

However, this rulemaking process has been far from simple. Two large electric utilities agreed that EVSE owners should not be treated as electric utilities, while two other electric utilities argued for the opposite. There were several other parties to the case, including environmental non-governmental organizations (NGOs), EV companies, and consumer rate advocates. Issues that remain to be resolved in additional hearings include cost allocation for any grid upgrades that may be required to accommodate new EVSE-related load, as well as new metering and health and safety requirements.

Each state PUC will likely require rule-making processes similar in nature to California's. These are time-consuming processes which may vary widely from state to state and municipality to municipality.

Resolving local issues in one way may complicate regional issues in another. This is a concern, especially in large metropolitan areas such as New York City or Washington, DC, where the interests of numerous states and municipalities will have to be accommodated. Rationalization of the range of regulations across the range of governmental entities will be a complex, difficult, and time-consuming process, which should not be underestimated for its potential to delay or deter the widespread market penetration of EVs. A summary of the above issues is seen Table 4.

Table 4 – Factors to Be Considered in the Installation of Public EVSE

Public Electric Vehicle Supply Equipment: Physical Installation Considerations

Location: Must be proximate to EV owners but must accommodate the parking needs of conventional vehicle owners at the same time. Public EVSE could be installed in parking lots or street sides.

Design: Should take into account disability laws, building and electric codes, and public safety. These may vary depending upon whether the EVSE is indoors or outdoors. EVSE installations will require a means of payment for charging services. Installations must take into account impact on local electric system, including thermal and voltage effects.

Fairness: Given the limited number of EVSE stations and the amount of time it takes to charge, the EVSE owners must determine a "fair" way to allocate charging time so that no single EVSE monopolizes a charger while others are waiting to charge EVs.

The building of an EV infrastructure raises many classic "chicken and egg" questions. Large-scale penetration of EVs cannot occur without widespread EVSE installations, but investment in such installations — both capital investment and the associated policy structures — makes little sense without assurances of a sizeable fleet of EVs.

The DoE is helping to "prime the pump" by providing funding for EVSE from two manufacturers: Coulomb Technologies and ECOtality (formerly eTec). These companies are running ChargePoint America and The EV Project, respectively, two programs designed to install public and private charging stations throughout the US, primarily on the east and west coasts.

An EVSE infrastructure is also an essential component of overall consumer acceptance. Convenience, reliability, and range-anxiety issues can all be resolved or exacerbated by the adequacy or lack thereof of this infrastructure, which has received relatively little serious national attention in spite of the new tax incentives for EVs, providing another example of a "chicken and egg" dilemma.

Table 5 highlights several financial models that could address the EVSE issue. The current model for The EV Project and ChargePoint America is "Public Pays," as much of the funding for these programs comes from money allocated to the DoE under the ARRA.[66]

Table 5 – EVSE Payment Options

Public Electric Vehicle Supply Equipment: Possible Financial Models

Public Pays: This would mean socializing the costs of EVSE across everyone in the city or township, on the argument that all of society benefits from EVs in terms of reduced air pollution. Costs could be defined to mean either the capital costs of the EVSE or both the capital costs and the electricity used by the EVSE. If the latter is not used, then the EVSE must be equipped with a technology that will allow EV owners to pay for the EVSE services. Insurance and operation and maintenance (O&M) would also be paid for by the public. Revenue from the EVSE would be used according to local regulations.

EV Owners Pay: All owners of EVs who make use of EVSE pay for the capital, insurance, and O&M costs of those EVSEs. This would only be feasible in cases where EV owners self-organize to form a financing group, and is highly reliant on individual bottom-up initiative as opposed to state or federal policy. The use of EVSE revenue would be determined by the EV owners.

Utilities Pay: EVSE and utilities both sell electricity, so there may be a natural alignment of interests in giving utilities responsibility for EVSE. Utilities would pay for insurance and O&M, and use the revenue as they see fit. It is not clear if utilities are interested in such an arrangement, since regulators might disapprove of the investment and force the utility to bear the entire cost. A preferable arrangement for the utility would allow it to include the cost of EVSE in its rate base, which, depending on the structure of the tariff, could be understood as a form of socializing EVSE costs.

EV Charging for Single-Family Residences

Even private, in-garage EVSE is more complex than it may initially appear. There is no standard amount of time required to charge a battery; instead, charging times are mainly a function of the amount of power the charger can deliver and the battery capacity, although charging times also vary according to battery chemistry.

Many home garages are currently wired for only 120-volt charging, which could result in long charging times — as long as 15 hours for an EV with a large battery,[67] although for PHEVs that can drive up to 20 miles on electricity, this time will be slightly less than six hours.[68] Discussions revolving around charging typically make reference to three levels of charging, summarized in Table 6.

Table 6 – EV Recharging Levels[69]

Charging Level	Voltage	Amperage	Power
Level 1	120 V AC	Up to 20 amps	Up to 2.4 kW
Level 2	240 V AC	Up to 80 amps	Up to 19.2 kW
Level 3	Not yet defined	Not yet defined	20 kW to 250 kW

Level 1 charging would be possible in most garages in the US with existing wiring and could be sufficient for vehicles with small batteries; these would typically be EVs with a low DOE.

EVs with a higher DOE require larger batteries; homes and garages may need level 2 charging in order to accommodate this activity. Not all homes, however, have wiring that would support level 2 charging. Upgrades could cost anywhere from $500 to $2,500, depending upon the wiring already in the home.[70] This adds cost and represents an additional hurdle for consumer acceptance of EVs with a high DOE.

To help defray the cost for early adopters, the DoE is providing free level 2 charging hardware and installation for the first 4,400 owners of the Chevy Volt, with installation services coming from either ChargePoint America or ECOtality.[71] In exchange for this service, EV owners must agree to anonymously provide usage information to their EVSE supplier. Symposium participants noted that home wiring upgrades currently take about 30 to 45 days, largely for getting requisite permits. Large-scale penetration of high DOE EVs would also raise workforce issues as it would require in-home installation by skilled electricians.

Level 3 charging, which is sometimes referred to as fast charging, is expected to operate at the highest power levels, although it is not yet commercialized and is largely still in the concept phase. Depending upon its configuration, it could provide an 80% recharge for a 30 kWh battery in less than 10 minutes.[72] This is proposed for use on roadsides, as the equivalent to an "EV gas station" and is expected to cost somewhere between $25,000 and $50,000 per unit.[73]

Standardization

In order to ensure that all EVs can charge using EVSE produced by different manufacturers, there must be a standard that governs the charging interface. Furthermore, as one symposium participant pointed out, the physical charging interface is important "because it's the thing the consumer touches and handles." To this end, the Society of Automotive Engineers (SAE) has created the J1772 standard to govern the physical power plug to EVs. This five-pin conductive charger will be used for level 1 and level 2 charging, as described in Table 6, and has a variety of safety features to prevent injury during charging.

The SAE is also producing other standards including J2836, which will be used by EVSE and car manufacturers to diagnose charging problems and J2847, which sets standards for EV-to-grid communication.[74] There are a variety of other standards[75] which govern power quality, methods for rating electric motor propulsion, and other EV-to-grid communication aspects.

An EV must be able to charge at any charging station in the US, regardless of the vehicle, EVSE, or metering manufacturer and how the utility sets rates for EV charging. It is important that all stakeholders in the EV design process — including auto manufacturers, utilities, and EVSE producers — determine and implement the same standards. This includes everything from physical charging interconnection to the wireless software that controls the charging.

While the US is on a pathway of standardization, this is not the case worldwide. One symposium participant pointed out that Germany, France, and Italy are each designing their own conductive EV rechargers. This could fragment the international market for EVs, especially in Europe.

Intelligent Grid

EV charging will place new demands on the electric grid. An EV using level 2 recharging, for example, would be expected to consume around 6.5 kilowatts (kW) of power, roughly equivalent to the peak power consumption of a typical home in certain regions of the US. As one participant pointed out, unlike a home, an EV moves around and may charge in different places throughout the day. Depending upon the distribution of transformers, just a few new EVs on a block could overload local electric capacity.

One participant noted that, in areas where demand for electricity is consistently high, such as in regions in the US that need year-round air-conditioning, transformers will likely be able to handle the additional load, assuming charging occurs overnight. Local infrastructure upgrades in regions of low or more variable demand may require upgrades to avoid issues related to overheating.[76]

Additional generation requirements are also an issue. If, for example, EV owners were to charge immediately after arriving home from work, the marginal power generated would likely be expensive and inefficient and have adverse environmental impacts. One study indicated that in the New York City metro area, if all projected plug-in EV owners were to charge concurrently within one hour, the additional load on the grid would be almost 300 MW.[77] This is equivalent to the capacity of a small power plant.

Independent System Operators (ISOs) are concerned about the impact of new EVs on their power grids, particularly lower voltage distribution grids. In order to help plan for any necessary upgrades, ISOs will need to know where new EVs will charge, but it is unclear how they will be able to reliably track new EV purchases in their regions. Some have speculated that it might be possible to work with the DMVs to obtain EV registrations, but legality and privacy issues would first have to be resolved.

In order to optimize usage and not overtax the grid, EVs will need to be “smart” about how and when they charge. Enabling this type of charging will require the range of standards outlined above as well as a great deal of collaboration between utilities and automakers — a relationship for which there is no history. The primary goal of this collaboration would be to design a system that encourages — with a great deal of certainty — EV users to charge their vehicles in off-peak electricity demand periods to the maximum extent practicable. This typically occurs from the late evening to the morning and varies slightly according to the season. It also raises equity issues for some EV users who, for example, work at night.

Definitions of “smart charging” vary. EVs may initially use an onboard timer to specify when charging starts, similar to what will be used in the Nissan LEAF. This will allow owners to program the car to charge during off-peak times, which are assumed to be understood by the owner.

Future technologies, in conjunction with a set of appropriate standards, might allow EVs to monitor real-time price signals from the utility and begin to charge when prices fall below a certain threshold. This would also allow the EV owner to set certain charging goals, for example, charging to 100% when the price is low, but only 50% when prices are high. Others have proposed charging signals that would allow charging based on the current load or availability of renewable energy. The latter would allow the realization of EVs charged almost entirely by renewable resources.

Some propose that smart charging be kept in the off-board EVSE. This raises yet another issue of standardization that will require cooperation between EVSE producers, automakers, and utilities.

Variations on smart charging technologies include concepts such as onboard software to monitor driving routes — and to automatically charge based on these routes — or allowing software to determine the charging scheme based on the input of a driver's daily schedule. Some symposium participants expressed skepticism about the interest of the average driver in such complicated charger configurations.

One widely discussed EV topic was Vehicle-to-Grid (V2G) technology. V2G proposes that the batteries in EVs which, like most cars, are parked for the majority of the day, be used to provide ancillary grid services to utilities. EVs could, for example, charge during off-peak hours, perhaps using renewable resources, and then provide power back to the grid, according to signals sent by the utility via a smart charging interface.

There have been many research papers written about V2G, but the consensus among symposium attendees was that V2G is not yet ready for commercial adoption, although reasons for this view were varied. Reasons included:

- *The complicated nature of such arrangements.* Because of the complex nature of such transactions, a third-party EV aggregator would likely be needed to "collect" EVs together and aggregate services to utilities.

- *The lack of a value proposition for consumers*, with some noting that the current market pricing structure precludes opportunities for "making money" from such sales. This may be due to market structures that do not sufficiently value the services that EVs could provide for the grid.

- *Design changes.* Some said that EVs might need to be designed differently, with changes to the electronic systems, in order to support certain proposed V2G services, such as regulation, which may require rapid switches before fully charging and fully discharging the battery.

Issues Summary: The charging infrastructure will play a key role in consumer acceptance of EVs, especially those with a high DOE. Although technical standards are currently in place to govern the physical EV charging interface, the standards for EV-to-grid communication are still undergoing revision. Utilities are interested in supporting EVSE installations but disagree over how this should be managed. Private, in-home EVSE may require wiring upgrades, which should be taken into the overall cost of an EV.

In order to avoid stressing the grid, EVs will need to charge intelligently, using off-peak electricity during the night. There are a variety of options for intelligent charging, many of which will require some form of communication between the grid and the EV. The deployment of this technology will depend upon collaboration between EV owners, utilities, EV manufacturers, and other stakeholders. Current standards-setting processes will play an important role in the development of this system.

ISOs currently have no accurate way of assessing where EV owners are on their distribution grids. The added load of EVs may result in more rapid aging-out of existing infrastructure and, in some places, will require the installation of additional transformers. The DoE funded EVSE program will provide some useful information to ISOs, but a long-term sustainable solution is required.

The degree to which government incentives are needed to finance EVSE development is an unresolved issue that will require thorough vetting by policy makers. Regardless, municipalities will need to ensure access to public charging by keeping it safe, reliable, and fair.

Panel Three Findings: Vehicle Infrastructure

Finding: The role of EV infrastructure and policies to support its development need significant analysis, planning, clarification, and innovation in order to enable significant market penetration of EVs. Uniform definitions, such as smart charging, should be developed and agreed to by requisite policy and standards-setting bodies.

Finding: Because the DOE of EVs is still unclear, it is difficult to determine how much or what type of infrastructure is needed to support EVs. There is agreement that the lack of public infrastructure will impede EV market penetration, but disagreement on timing and degree of public support for its development.

Finding: Critical regulatory issues will have to be resolved to enable EVSE installation, both in homes and for public use. State PUCs will have to determine if and how to regulate public EVSE.

Finding: Harmonization of regulations will have to occur between government jurisdictions to ensure ease of travel and reliability of the system.

Finding: EV charging will have an impact on the grid. The extent of that impact depends on the existing transmission and distribution infrastructure in areas where EVs are being purchased. It may be necessary to upgrade transformers for residential or commercial customers' installation of EVSE. It is not clear how these upgrades should be paid for and who specifically should bear the cost.

Finding: Assuming significant market penetration of EVs, access to public EVSE must be fair and widely available. Municipalities will need to ensure that rules and regulations are in place on charging time, charging order, etc., and will need to penalize those who monopolize charging facilities.

Panel Four: EV Policy

Participants generally agreed that:

- Internalizing externalities into transportation options — climate change impacts, air pollution, security costs, and economic loss due to oil dependence — cannot occur without government intervention in the transportation sector to ensure that consumer and producer interests are aligned with a set of public goods;

- This was a desirable policy objective;

- A relatively rapid policy response to these issues was needed.

Where opinions diverged, however, was on the appropriate government role in technology development. The technology agnostics supported mechanisms to provide the marketplace with technology options, leaving consumers and industry as the ultimate arbiters on investments and choices. These participants stressed the need to avoid picking winners, highlighted previous failures in this regard, and urged the use of a range of policy mechanisms to provide the marketplace with options.

The technology advocates favored more direct intervention by the government in support of specific electrification technologies in order to overcome social, cultural, and economic hurdles to achieve the maximum social benefit. Table 7 documents the policy options discussed by the participants differentiating between those promoted by the technology agnostics and the advocates.

Table 7 – Policy Options

Policy Strategy	Policies to Improve the Fuel Efficiency of New Vehicles	Policies to Improve the Carbon Content of Fuels	Policies to Drive Consumer Acceptance
Agnostics	• Carbon tax • Carbon cap-and-trade system • Gas tax • CAFE standards • Feebates	• Carbon tax • Carbon cap-and-trade system • Gas tax • Low-carbon fuel standard	• Land use policies • Driver education • Public information campaign
Advocates	• Tax credit for PHEV and EV purchases • Tax credit for natural gas vehicle purchases • R&D • Zero-emissions requirement	• Subsidies for biofuel production • R&D • Incentives for low-carbon fuel infrastructure	• EV infrastructure investment subsidies • Electricity rate schemes favoring EV adoption and ancillary grid services

There was consensus on a central point: the nation lacks a coherent energy policy. The prevailing view was that policy makers have eschewed coherence and cohesion in favor of a collection of a disconnected array of policy choices that represent political but not policy balance. Participants also agreed that erratic approaches to market conditioning — which at times dictate technology choices and at other times, avoid them — were inefficient.[78]

Alternative Vehicle Incentives and Programs

Via statute, Congress has endorsed numerous subsidies for vehicle electrification beginning with the EPAct, continuing in the EISA and in the EESA, and culminating in the ARRA.[79] Through tax credits for the purchase of PHEVs and BEVs and the allocation of funds for the development of battery manufacturing facilities, the federal government has clearly signaled that it, as a matter of policy, favors electrification of the nation's transportation system. Today, consumers who purchase EVs or PHEVs with a minimum 5 kWh battery capacity are eligible for a $2,500 tax credit and an extra $417 for each additional kWh of battery capacity, with a maximum credit of $7,500.

There are also subsidies in place for NGVs, as well as fuel mandates to spur the development of a biofuels industry.[80] It is not apparent that these policy choices, and the suite of EV policies, have been rationalized in any way. This could be critical for ease and reliability of interstate and inter-regional vehicle travel in the future, assuming significant market penetration of each of these transportation options. The limited success of government intervention to date was noted by participants although concerns were voiced about the consistency of the government's commitment over time. Table 8 provides a general overview of the federal government support for EVs, NGVs, and ethanol.

Table 8 – A Sampling of Federal Support for Vehicle Technologies

	Program	Legislation	Description	Cost
Batteries, Infrastructure and Manufacturing Assistance	Advanced Vehicle Technology Program	American Recovery and Reinvestment Act	Provides direct investment for battery and infrastructure manufacturing deployment — $2.5 billion of which went to battery and component manufacturing plants	$5 billion
	Advanced Technology Vehicle Manufacturing Loan Program	Energy Independence and Security Act 2007	Direct loans to Nissan, Tesla, and Fisker for EV facilities in Delaware, Tennessee, and California. Manufacturers are eligible for direct loans of up to 30% of the cost to reequip, expand, or establish manufacturing facilities	$2.6 billion
	Battery Research and Development Grants from ARPA-E	American Recovery and Reinvestment Act	Direct grants for high-risk/high-reward research on next-generation batteries, specifically ultra-capacitors and metal-air batteries	$80 million
EV Deployment	Plug-In Hybrid Tax Credit	Energy Policy Act of 2005, adjusted with the Energy Independence and Security Act of 2007, Emergency Economic Stabilization Act of 2008, and American Recovery and Reinvestment Act of 2009	For batteries of at least 4 kWh in capacity, this program offers a $2,500 income-tax credit with an additional $417 for each added kWh of capacity, with a maximum credit of $7,500 for up to 200,000 vehicles	$1.5 billion
	Vehicle Electrification Initiative	American Recovery and Reinvestment Act	Provides grants to 11 localities for deployment and integration, includes the cost of vehicles, infrastructure, and workforce education programs	$400 million
Ethanol	Volumetric Ethanol Excise Tax Credit	American Jobs Creation Act 2004, adjusted in the Farm Bill 2008	Provides $.45 per gallon subsidy for any blending of ethanol into petroleum products	$5 billion
Natural Gas Vehicles and Infrastructure	Income Tax Credits for Alternative Fuel Vehicles	Energy Policy Act of 2005	Provides an income tax credit for the purchase of a natural gas vehicle	$2,500 to $32,000 per vehicle
	Income Tax Credits for Alternative Fuel Infrastructure	Energy Policy Act of 2005	Provides an income tax credit for the installation of natural gas refueling equipment	$30,000 for large station installation and $1,000 for household

Tax credits for PHEV and EV purchases and the funding for battery manufacturing plants are enabling a nascent but growing battery market sufficient to attract investments from major chemical companies.

A new policy regime must bring cohesion to this environment through the clear portrayal of goals. With respect to the transportation system, participants agreed that policies:

- must support technology development to improve the fuel efficiency of new vehicles;
- reduce the carbon content of fuels; and
- perhaps, most importantly, earn consumer acceptance.

Several participants urged sustained federal subsidies in order to maintain this momentum. Others were concerned by the "grab bag" of policies and their lack of analytical underpinnings, creating significant potential for unintended consequences, major system gaps, and wasteful spending.

First Step: A Carbon Price

Though participants disagreed on the specifics of implementation, there was consensus on the need to establish a carbon price in order to efficiently internalize the environmental and security externalities in the transportation system. The permutations of such a policy that were discussed include an economy wide carbon cap-and-trade system, a carbon tax, and a gas tax. Specifically, participants proposed a $1 gasoline tax and a $20 per ton carbon tax.

Briefly, a cap-and-trade system is a market-oriented approach that puts a cap on carbon emissions, either economy-wide or by sector, and allows producers to buy and sell emissions allowances. The price of the emissions allowances would vary according to the market.

Under a cap-and-trade system, the emissions limit is set and the price of emissions fluctuates. The opposite is the case for a carbon tax in which the price per unit of emissions is fixed, but the level of emissions could fluctuate. A gas tax would be an added surcharge to the price of a gallon of gas.

These three policy options are consistent with the approach that is technology agnostic for reducing carbon emissions on a least cost basis. The theory is that the market will prefer technologies that most efficiently meet the environmental standards. Participants did express concern that a cap and trade on transportation would not result in carbon reductions in the transportation sector because of its inadequacy for affecting global oil markets and thus, the underlying price of gas.

Each of these policy options provides benefits in support of the overarching policy of transportation electrification. As discussed earlier, batteries for EVs are expensive. Theoretically, these costs can be partially recouped in fuel savings over the vehicle's life span. In Europe, high gasoline taxes place vehicle electrification technologies on a cost-competitive basis. In the US, however, the current average fuel tax, including state and federal taxes, is 47 cents, a level that is insufficient to ensure cost recoupment for EV owners.[81]

Gas tax level options were discussed including a $1 per gallon gas tax to send a clear signal to the market. Such a tax could be implemented in 10-cent increments over 10 years, amounting to a $1 per gallon gas tax by 2020.[82]

Some participants favored a specific type of gas tax indexed to carbon content, over a carbon tax or a cap-and-trade system because of concerns outlined here, noting that analysis suggests that the resulting price of emissions permits in a cap-and-trade system would be passed on to consumers in the form of moderately higher gas prices.[83]

With respect to mobile sources, questions were also raised about the point of regulation of vehicular carbon emissions. Should they be regulated at the tailpipe or on the basis of the full life cycle of a vehicle? If the policy choice is the latter, better carbon-accounting capabilities are needed to assess full life cycle GHG emissions.[84]

Participants acknowledged that a carbon tax or a cap-and-trade system would reduce emissions in the electricity sector, ensuring reductions in the well-to-wheels emissions for EVs. As previously noted, analysis suggests that under the current resource mix in the power sector, EVs on a well-to-wheels basis emit less CO_2 than conventional vehicles.[85] However, significant emissions reductions do not occur until the fuel mix for the power sector is much cleaner. A carbon price or cap-and-trade system would begin to decarbonize the electricity sector, with a corresponding reduction in emissions allocated to EVs.

All three of these options represent a possible source for significant government revenues. While a number of options for allocation of these funds were discussed, there was no consensus by participants on how these revenues should be spent. The following captures the range of suggestions:

- Revenues should go directly to reduce the deficit.
- Revenue gains from a carbon price should be applied to equivalent reductions in income or payroll taxes in order to return the money to the consumers. Increases in gasoline prices would disproportionately impact low-income consumers, an undesirable outcome that should be mitigated in policy.[86]
- Revenues should be dedicated to developing the technologies, infrastructure, and policies to electrify the LDV fleet.

Grid Policies for EVs

As noted, EVs could have a significant impact on the load requirements of the electric grid, particularly at peak times when emissions may be greater depending on the generation unit and fuel mixes. Wide-scale deployment of EVs could also entail adding capacity which, depending on the fuel, could result in increased GHG emissions.

Participants briefly discussed time-of-use pricing to incentivize off-peak charging. There was some skepticism centering on technical limitations for implementation of such an option. It was suggested that time-of-day pricing might be a more realistic and feasible option. Advances in smart-metering technology would be required to enable either of these billing options.

In addition, vehicle electrification poses a problem to electricity providers in decoupled markets. Under decoupling, an electric utility is incentivized by its PUC to reduce power sales. Typically, this would mean a loss in profit for the utility, but under decoupling schemes, the utility's profits are no longer solely a function of power sales but are instead tied by the rate makers to reductions in power use, increases in the number of new consumers, and several other factors.

Charging an EV requires a significant amount of power, and with substantial market penetration of EVs, decoupled utilities could expect to be penalized for the associated increase in power sales. Rate makers and PUCs will need to work with utilities to allow power sales to EVs without penalizing the utility for those extra sales.

Policies to Improve the Fuel Efficiency of New Vehicles

Performance Standards

Participants largely agreed that performance standards offer the most effective, least costly, and the method that is the most technology agnostic as regards to improving the fuel efficiency of new vehicles. They do however raise equity issues, can be manipulated, and — because they are static — tend to freeze efficiency achievements in place irrespective of technology advances.

In 1975, Congress passed the first Corporate Average Fuel Economy (CAFE) standard, requiring that automobile manufacturers produce a fleet that meets an average fuel economy standard. With the exception of some minor tinkering between 1975 and 1980, this standard remained fixed until 2007, with the passage of EISA. EISA increased the standard by 40%, requiring a 35 miles per gallon (mpg) standard for LDVs by 2020.[87]

In 2009, the Obama Administration, through the Environmental Protection Agency (EPA) rulemaking pursuant to the Clean Air Act, accelerated this goal, requiring 35.5 mpg by 2016.[88] Participants applauded this move by the Obama Administration but called for ongoing increases in vehicle efficiency standards, noting that this was the best near-term, achievable option for reducing emissions from the transportation sector. Indeed, one participant suggested that a 50 mpg standard be required to achieve the desirable carbon mitigation and oil consumption reductions.

CAFE standards are not, however, a perfect policy mechanism. Today's CAFE standards count EVs and PHEVs as zero-emissions vehicles, drastically overstating the environmental benefits of these technologies.[89] Similarly, the current CAFE standards provide credits for flex-fuel vehicles, even though empirical evidence suggests that these vehicles are rarely operated on alternative fuels.[90] These manipulations in favor of certain technologies diminish the agnostic aspects of CAFE standards.

A concern was raised about an unintended consequence of decreased gasoline consumption. Currently, revenues from federal gasoline taxes finance the expansion and maintenance of the interstate highway system. These revenues will decline along with gasoline consumption and a new source of revenues will be necessary to fund maintenance or expansion of the interstate highway system.

Feebates

Participants also discussed feebates as a policy option for improving vehicle efficiency. A feebate combines a surcharge on low-mileage vehicles with a rebate to consumers for purchases of fuel-efficient vehicles. Feebates rely more on market signals than do performance standards, allowing them to better align producer and consumer motivations with overarching policy objectives, sending a stronger market signal about the social value of efficient transportation as a matter of US policy.

A feebate will likely achieve the best results when it is used not in lieu of CAFE standards but complementary to them.[91] One shortcoming of CAFE standards is that they provide insufficient deterrence for purchases of low-mileage vehicles. By setting an incrementally higher marginal price for inefficient vehicles, a feebate would add further disincentives for such purchases. Further, because CAFE standards are based on average fleet efficiencies, manufacturers can "cross subsidize" various models and still meet overall efficiency requirements.

Depending on the pivot point of the feebate — the fuel-efficiency point at which a vehicle shifts from rebate eligible to fee eligible — the policy can be designed to increase revenue, decrease revenue, or be revenue neutral.[92] However, this designation will have to be closely monitored as consumer and producer preferences evolve.

Theoretically, consumers will begin to shift toward more fuel-efficient vehicles, increasing the number of rebates that will have to be provided. Funds-in must equal funds-out so the pivot point must be evaluated regularly and adjusted to approximate the average fuel economy of the vehicle fleet in a given year.[93] This poses a timing issue relative to the schedules of vehicle manufacturers which require longer than a year's lead time. One solution proposed by Professor John Heywood's lab at MIT is to set fuel economy windows for the pivot points several years in advance to give manufacturers a rough idea of where the pivot point would be set.

One example of a feebate system, also proposed by Professor Heywood's lab, is to set the initial pivot point at 39 gallons per every 1,000 miles. Based on the vehicles on the market in 2008, 60% of all consumers would be eligible for a rebate. Heywood recommends that the fee and rebate vary by $120 for each gallon per 1,000 miles. This policy would reduce the fuel consumption of the average new car by 30% over a 15-year period.[94]

Low-Carbon Fuel Standards

A low-carbon fuel standard operates like a cap-and-trade program, limiting the carbon intensity of the fuel supply and allowing individual fuel producers to buy and sell permits for higher intensity fuel. Thus, a low-carbon fuel standard would require oil companies to reduce the carbon intensity of their product by mixing in lower carbon fuels such as biofuels. Alternatively, oil companies could buy credits from lower carbon fuel providers.

Such a standard would apply to the electricity that powers EVs as well. The effects on vehicle electrification would vary across areas with different electricity generation mixes.

A low-carbon fuel standard would result in higher prices for more carbon intensive fuels. One participant endorsed such a standard as a strong message to the marketplace, remaining technology agnostic while driving innovation in the fuel sector.

Resistance to a low-carbon fuel standard centered on the complexities of its implementation schemes. Regulating the quality of a given product seems much easier than regulating the quality of the goods that make up a product.

Zero-Emissions Requirement

California, along with 10 other states, has mandated that a certain number of zero-emissions vehicles be on the road by a given date. Specifically, California has required that 7,500 fuel cell vehicles, 12,500 EVs, and 58,000 PHEVs be on the road by 2014.[95] To help the manufacturers sell this number of vehicles, the state provides additional tax credits, hoping to spur investment in new technology.[96]

Mandates of this type raise issues about what happens and who pays if the mandates are not met. It is also very specific in the types as well as numbers of favored technologies. It is unclear what type of infrastructure and regulatory regime is required under such a mandate.

Incentives for Low-Carbon Fuel Infrastructures

Non-liquid alternatives to gasoline — including electricity, natural gas, and hydrogen — require new production and distribution infrastructures, adding to the difficulties of wide-scale deployment of EVs.[97] Some participants favored policies to subsidize the development of electricity and hydrogen fueling stations. Another policy option that was discussed was mandating that gas stations provide access to electricity recharging and hydrogen refueling.[98]

Research, Development, and Demonstration

Participants emphasized the need for greater government support of both basic science and materials science research. One participant noted that developments in basic science research serve as the cornerstone for technological advancement by industry[99]. Further, technological advances in battery and materials science to reduce costs and improve the performance of EVs were viewed as essential.

Participants also stressed the importance of federal support for funding demonstration vehicle electrification projects. This was also viewed as essential for resolving the myriad systems issues associated with the integration of EVs; the electric grid; vehicle manufacturers; and federal, state, and local regulators. Projects would need to engage and encourage the support of the necessary stakeholders: state and municipal governments, local public utility commissions, local utilities, and large employers.[100] A demonstration program would provide critical information to planners engaged in systems development and reengineering.

Increasing Consumer Acceptance

Consumer acceptance concerns pervaded the discussion. Throughout the symposium, participants regularly acknowledged that the success or failure of vehicle electrification would be determined by the ability of government and industry to encourage consumer acceptance. This acceptance can take two forms.

First, consumer acceptance requires that manufacturers produce a good that consumers can both afford and enjoy. This places the burden of acceptance squarely on the backs of product manufacturers.

Consumer acceptance can also be achieved through the conscious altering of consumer preferences. This can be done in a variety of ways, first and foremost by the tax code or other policy tools which internalize the externalities into the cost of the vehicle and its fuel sources. The government can play a role by altering, through policy, the notions of convenience, responsibility, and a focus on the social costs and values associated with EVs.

Participants acknowledged the difficulties faced by EVs in achieving consumer support — absent significant subsidies — sufficient to enable a wholesale and rapid transformation of the transportation sector. Large-scale penetration will require a reduction in the total cost of ownership. Some of the policies discussed above will help lower this barrier.

Also, consumers will have to accept battery life uncertainty and range limitations. Uncertainty about the life span of the battery has prevented manufacturers from offering the same 100,000-mile drive-train warranty that they offer for conventional vehicles. Participants called for further analysis of consumer behavior to identify how consumers feel about these concerns.

Cost and technology only go so far. Changing consumer preferences is essential. Much can be done to assist consumers in understanding the overall value of EVs as well as their implications for climate change, energy security, balance of trade, and enhanced foreign policy options. One option: more efficient land use policies and reduction in urban sprawl. Reduction in sprawl in tandem with greater access to public transportation will result in fewer vehicle miles traveled, and perhaps, accordingly, a diminution of range anxiety.

Similarly, driver education could play a role in enlightening individuals about the direct and in some instances, profound impacts EVs can have on addressing environmental and energy security goals.[101] Today, all new vehicles are required to have fuel economy labels on them.[102] Standardizing this presentation and making it accessible online could encourage consumers to take fuel economy more seriously.[103] Finally, a public information campaign to teach new drivers fuel-efficient driving behavior could enable consumers to make the most of the fuel that they consume.

Need for a Coherent, Simple Approach

Over the course of the symposium, numerous policy recommendations were put forward. By the end, participants acknowledged that some of the options call for unprecedented expenditures, were too complex, or both. Policies and messages needed to be simplified. Further, proper cost-benefit analysis of these policies must be done to determine the most cost-effective solutions.

Participants did however acknowledge the urgency of action in the transportation sector, particularly for meeting environmental and energy security policy goals. One participant noted that the wholesale transformation of the transportation sector will require a set of goals and a highly refined strategy based on a foundation of sound analysis and understanding of the consequences of a suite of actions. Most participants also agreed that the environmental and energy security challenges facing the US today require the aggressive pursuit of several paths, without picking one winner.

Issues Summary. There was consensus on a central point: the nation lacks a coherent energy policy. The prevailing view was that policy makers have eschewed coherence and cohesion in favor of a collection of a disconnected array of policy choices that represent political but not policy balance. Participants also agreed that erratic approaches to market conditioning — which at times dictates technology choices and at other times, avoids them — were inefficient.

Participants differed on the extent of government intervention acceptable in meeting the environmental and energy security challenges that face the country today. Some advocated for a technologically agnostic approach in which the government does not pick the winners. Others favored greater government intervention, asserting that certain technologies faced greater social, cultural, and economic hurdles requiring added support to achieve maximum welfare.

Though participants disagreed on the specifics of implementation, there was consensus on the need to establish a carbon price in order to efficiently internalize the environmental and security externalities in the transportation system. The permutations of such a policy that were discussed include an economy-wide carbon cap-and-trade system, a carbon tax, and a gas tax. These views are summarized in Table 7.

Panel Four Findings: EV Policy

Finding: There is a lack of cohesion and clearly defined policy goals in the current assortment of subsidies that comprise US energy policy. A unified energy policy is needed that appropriately defines, analyzes, and sequences public investments and incentives. Electrification of the transportation system would benefit from a more thoughtful approach to what amounts to major nationwide changes.

Finding: Stimulus funding has created lots of momentum for technological innovation. One challenge moving forward will be maintaining this momentum when the funding runs out.

Finding: For EV technologies to more rapidly and efficiently scale, there must be a price on carbon in the form of a carbon tax, cap-and-trade system, or gas tax, though the relative effectiveness of these three options was contested.

Finding: A unified policy must achieve three distinct goals: improve the fuel efficiency of new vehicles, reduce the carbon content of fuels, and drive consumer acceptance.

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ABBREVIATIONS / ACRONYMS

ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Reinvestment Act of 2009
BEV	Battery Electric Vehicle
bpd	Barrels per Day
CAFE	Corporate Average Fuel Economy
CCS	Carbon Capture and Sequestration
CO_2	Carbon Dioxide
cf	Cubic Feet
DMV	Department of Motor Vehicles
DoE	Department of Energy
DOE	Degree of Electrification
EESA	Emergency Economic Stabilization Act of 2008
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
EPRI	Electric Power Research Institute
EREV	Extended Range Electric Vehicle
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IPCC	International Panel on Climate Change
ISO	Independent System Operator
kW	Kilowatts
kWh	kilowatt-hour
LDV	Light-duty Vehicle
Li-ion	Lithium-ion
mbpd	Million Barrels per Day
MDU	Multiple Dwelling Unit
MITEI	MIT Energy Initiative
mpg	Miles per Gallon
NATO	North Atlantic Treaty Organization
NGO	Non-Governmental Organization
NiMH	Nickel Metal Hydride
NGV	Natural Gas Vehicle
NOC	National Oil Companies
NOx	Nitrogen Oxide
NRC	Natural Resource Council
NRDC	Natural Resources Defense Council
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PHEV	Plug-in Hybrid Electric Vehicle
ppm	Parts per Million
PUC	Public Utility Commission
R&D	Research and Development
SAE	Society of Automotive Engineers
SO_x	Sulfur Oxide
U	Uranium

APPENDICES

A. Symposium Agenda

B. List of Participants

C. White Paper, Edited by Ronald E. Minsk, *Plugging Cars into the Grid: Why the Government Should Make a Choice & Policies to Promote Deployment of Grid-Enabled Vehicles*

D. White Paper, Mark Duvall, Electric Power Research Institute, *Discussion of the Benefits and Impacts of Plug-In Hybrid and Battery Electric Vehicles*

E. White Paper, Tony Markel, National Renewable Energy Laboratory, *Plug-in Electric Vehicle Infrastructure: A Foundation for Electrified Transportation*, April 8, 2010

F. White Paper, Daniel Sperling with Deborah Gordon, Institute of Transportation Studies, *Electric Vehicle Policy*, April 7, 2010

SYMPOSIUM AGENDA

The Electrification of the Transportation System: Issues and Opportunities

Massachusetts Institute of Technology
April 8, 2010

9:30–9:35 **Welcome**
Ernest Moniz, MIT, Symposium Chair

9:35–10:30 **Framing the Issue: Why Electrification Matters**
Ronald Minsk, Securing America's Future Energy
Richard Jones, International Energy Agency (IEA)
John Heywood, MIT

10:30–12:00 **Panel**
Vehicle Technologies

Chair:	John Wall, Cummins
White Paper Author:	Mark Duvall, Electric Power Research Institute (EPRI)
Discussant #1:	Donald Hillebrand, Argonne National Laboratory
Discussant #2:	Lawrence Burns, Columbia University
Discussant #3:	Alan Crane, National Research Council

12:00–1:00 Lunch

1:00–2:30 **Panel**
Infrastructure

Chair:	Michael Telson, General Atomics Corp. (GA)
White Paper Author:	Tony Markel, National Renewable Energy Laboratory (NREL)
Discussant #1:	Scott Williams, Coulomb Technologies
Discussant #2:	William Mitchell, MIT
Discussant #3:	Marija Ilic, MIT

2:30–2:45 Break

2:45–4:15 **Panel**
Policy Option

Chair:	Philip Giudice, Massachusetts Department of Energy Resources
White Paper Author:	Daniel Sperling, University of California, Davis
Discussant #1:	Richard Kolodziej, Natural Gas Vehicle Coalition
Discussant #2:	Luke Tonachel, Natural Resources Defense Council (NRDC)
Discussant #3:	John B. Hess, Hess Corporation

4:15–5:00 **Discussion/Wrap-Up**

Chair:	The Honorable David McCurdy Ernest Moniz and John Deutch, MIT

LIST OF PARTICIPANTS

The Electrification of the Transportation System: Issues and Opportunities

Massachusetts Institute of Technology
April 8, 2010

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Cynthia Barnhart	MIT	
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Daniel C. Cohn	MIT Energy Initiative	Discussant
Alan Crane	National Research Council	
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Fernando de Sisternes	MIT Sloan Automotive Laboratory	
John Deutch	MIT	Speaker
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Michal Ilana Freedhoff	Office of Rep. Edward J. Markey, US House of Representatives	
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Howard J. Herzog	MIT Energy Initiative	
John Hess	Hess Corporation	Discussant
John Heywood*	MIT	Speaker
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Donald Hillebrand	Argonne National Laboratory	Discussant
John Howe	Verenium	
Marja Ilic	Carnegie Mellon University	Discussant
Henry (Jake) Jacoby*	MIT	
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Richard Kolodziej	Natural Gas Vehicle Coalition	Discussant
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Tony Markel	National Renewable Energy Laboratory	Speaker
The Honorable David McCurdy	Alliance of Automobile Manufacturers	Chair
Ronald Minsk	Securing America's Future Energy	Speaker
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Richard Schmalensee	MIT	
Daniel Sperling	University of California, Davis	Speaker
Gregory C. Staple	American Clean Skies Foundation	
Carol Sturman	Sturman Industries	
Eddie Sturman	Sturman Industries	
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Borden Walker	Hess Corporation	
John Wall	Cummins	Chair
John Williams	MIT	
Scott Williams	Coulomb Technologies	Discussant
Stephen Zoepf	MIT	

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**PLUGGING CARS INTO THE GRID:
WHY THE GOVERNMENT SHOULD MAKE A CHOICE &
POLICIES TO PROMOTE DEPLOYMENT OF GRID-ENABLED VEHICLES**

Edited by Ronald E. Minsk[1]

Modern American life is premised on the assumption that inexpensive oil will be available forever to fuel our transportation system. Our vehicles, our jobs, and even the structure of our communities all depend on reliable supplies of affordable oil. Yet growing worldwide demand for oil and tightening supplies strongly suggest that the days of cheap, plentiful oil are over. Because we consume so much oil, which is so highly valued and for which we have virtually no substitutes in the short-term, price volatility in the world oil market inflicts significant economic damage on the United States. Our dependence on oil has been equally damaging beyond our shores, constraining our conduct of foreign policy and placing significant operational demands on our military.

Oil price volatility is a result of highly inelastic short-term demand, geopolitical instability in oil producing nations, inadequate investment in production capacity, and surging demand in emerging market nations. It is exacerbated by a classic market failure—oligopolistic behavior by nations participating in an oil producers' cartel. Unfortunately, traditional antitrust remedies are not available because the conspirators are sovereign nations. Unable to address the supply side of the problem, we are left to examine the demand side of the equation.

In order to escape the severe economic consequences of oil price volatility, it is necessary to electrify the short-haul transportation system. Electrification offers several advantages over the status quo: using electricity promotes fuel diversity; electricity is generated from a domestic portfolio of fuels; electricity prices are less volatile than oil and gasoline prices; using electricity is more efficient and has a better emissions profile than gasoline; using electricity will facilitate reduction of greenhouse gas emissions; and electricity is a low-cost alternative. We also observe that electricity is superior to other practical alternatives to petroleum to fuel the short-haul transportation system—natural gas, hydrogen, and biofuels—for many reasons, both economic and scientific.

Because of the advantages that they offer, it is likely that we will ultimately transform our short-haul ground transportation fleet to grid-connected vehicles. Though such vehicles are uneconomic in the United States at the present time, they are more competitive in Europe because of the high price of fuel, and are easier to transition to in China, because of the government's control over the economy and the absence of a car culture in which drivers have expectations that their cars can match the characteristics of internal combustion engine-powered vehicles. Accordingly, the government should implement policies to actively promote the development and deployment of technology to electrify the short-haul transportation system as part of an effort to reduce the economy's petroleum intensity, thereby enhancing our nation's national and economic security, and to avoid falling behind our major economic competitions in a transition that is nearly certain to occur.

I. THE AMERICAN OIL ECONOMY

For over a century, plentiful cheap energy has driven American economic growth. In one sense, this does not differentiate our nation from almost any other in modern economic history. Since the early days of the Industrial Revolution, economic growth has been yoked to energy

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[1] [1] This paper, edited by Ronald Minsk, is a condensed version of two other papers: 1) "Plugging Cars Into the Grid: Why the Government Should Make a Choice," published in the December, 2009 Energy Law Journal, coauthored by Ronald E. Minsk, Sam Ori and Sabrina Howell; and, 2) The Electrification Roadmap, published by the Electrification Coalition in November 2009, of which Ronald Minsk was one of several coauthors.

demand growth. As economic activity increases, the need for energy increases as well. After all, at its most basic level, energy is simply the ability to do work. And economic growth does not come without work.

Yet the United States is a special case. The United States is responsible for twenty-three percent of the world's daily oil consumption, twenty-two percent of daily natural gas consumption and seventeen percent of daily coal consumption.[2] Of every 100 kilowatt hours of electricity generated each day in the world, twenty-three percent are generated in the United States.[3] Our cities, our culture, and our society were built on the assumption that energy—and the fuel to make it—would be practically limitless and indefinitely cheap. And for the most part, we continue to live that way today. This is particularly true in the case of petroleum.

By 1900, U.S. oil production had been ongoing for more than forty years, initially for use as an illuminant. By 1900, annual U.S. oil production was roughly 63.6 million barrels.[4] By 1905, it had more than doubled to 138 million barrels.[5]

The growth of the oil industry laid the groundwork for what would eventually become its most reliable customers—transportation in general, and the internal combustion engine in particular. In the United States, vehicle registration rose from 8,000 in 1900 to 944,000 in 1912.[6] By 1929, there were more than 23 million vehicles and 140,000 gas stations across the nation.[7]

Over time, vehicle ownership soared ever higher as Americans moved away from overcrowded urban environments to enjoy the benefits of cleaner, less dense suburbs. Passage of the G.I. Bill of Rights[8] accelerated the growth of the suburbs and the need for automobiles. Then, the federal government built a national highway system[9] and Americans began to hit the roads en masse every summer. As of 2007, there were 844 vehicles for every 1,000 people in the United States compared to 426 in the United Kingdom, 543 in Japan, and thirty in China.[10] It is not surprising, therefore, that there are few recurring phenomena that influence global petroleum prices more heavily than the so-called "summer driving season" in the United States.[11]

There were bumps along the road as the American oil economy expanded in size and scope. The 1970s ushered in the rise of the Organization of the Petroleum Exporting Countries' (OPEC) power, the Arab Oil Embargo, and the Iran-Iraq War. These geopolitical disruptions resulted in skyrocketing oil prices, and initial public policy responses in the United States often only exacerbated problems. Gas lines, rationing, stagflation, and "turning down the thermostat" were defining aspects of the 1970s that seemed to significantly—if not permanently—alter views about oil consumption, in government and around the country.

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2. BP Statistical Review of World Energy 2009, at 41 (2009), *available at* www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2009_downloads/statistical_review_of_world_energy_full_report_2009.pdf.

3. DOE, EIA, *World Total Net Electricity Generation, 1980-2006*, at Tbl. 6 (2006), *available at* www.eia.doe.gov/pub/international/iealf/table63.xls.

4. DOE, EIA, *Petroleum Navigator*, http://tonto.eia.doe.gov/dnav/pet/hist/mcrfpus1a.htm, (last visited Sept. 16, 2009).

5. *Id.*

6. United States Department of Commerce, Bureau of the Census, Statistical Abstract of the United States (2009), *available at* www.allcountries.org/uscensus/1027_motor_vehicle_registrations.html.

7. *Id.* at 191-92.

8. Servicemen's Readjustment Act, Pub. L. No. 78-346**,** 58 Stat. 284 (1944).

9. National Interstate and Defense Highways Act, Pub. L. No. 84-627, 70 Stat. 374 (1956).

10. DOE, Office of Energy Efficiency and Renewable Energy (EERE), Vehicles Technology Program, *Changes in Vehicles per Capita Around the World* (June 29, 2009), *available at* www1.eere.energy.gov/vehiclesandfuels/facts/2009_fotw577.html.

11. DOE, EIA, *A Primer on Gasoline Prices*, at 2 (2006), *available at* www.eia.doe.gov/bookshelf/brochures/gasolinepricesprimer.

The Energy Policy and Conservation Act of 1975 mandated an improvement in the efficiency of the American automotive fleet.[12] And the Fuel Use Act of 1978 was primarily responsible for reducing petroleum use in the electric power sector from fifteen percent in 1975 to four percent in 1985.[13] All told, the petroleum intensity of the U.S. economy fell by thirty-five percent between 1973 and 1985. Between 1973 and 1995, the difference was forty-five percent.[14] But only a few years later, it was easy for most Americans to view the events of the 1970s as one-off perturbations. Disagreements among OPEC members led to an oil price collapse by 1985.[15] Crude oil was discovered in Prudhoe Bay and the North Sea, adding a much-needed boost to global oil supplies and placing further downward pressure on prices.[16]

With lower prices and new discoveries, oil market volatility posed a minimal threat in most American's minds by the end of the 1980s. Efforts to increase efficiency fell by the wayside.[17] And with oil prices at such low levels, most international oil companies scaled back their investments in developing new reserves, believing such efforts to be unprofitable in the short-term.[18, 19] In many ways, the 1990s served to reinforce these beliefs. Despite turmoil in Kuwait and Iraq and the resulting erosion of OPEC spare production capacity for several years,[20] for most of the period between 1993 and 2002 global oil production capacity stayed well above global oil demand, and prices were generally low and stable.[21, 22]

Change, however, was on the horizon. Many of the efficiency gains of the 1980s were reversed with the explosion in popularity in the United States of sport utility vehicles, whose viability was premised, in significant part, on the availability of cheap oil.[23] But the 1990s were perhaps the last decade of "easy oil." By 2008, almost 100 years to the date after Ford introduced "the car that put America on wheels," Americans were confronted with the possibility that there was a limit to the seemingly endless flow of oil that had for close to a century supported our mobile lifestyle.

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12. Energy Policy and Conservation Act, Pub. L. No. 94-163, 89 Stat. 871 § 301 (1975) (codified at 15 U.S.C. §§ 2001-12 (1975)).

13. DOE, EIA, *Annual Energy Review 2008*, at 230 (2009), *available at* www.eia.doe.gov/emeu/aer/pdf/pages/sec8_8.pdf [hereinafter, *Annual Energy Review 2008*].

14. Calculated by authors based on data from BP Statistical Review of World Energy 2009, Historical Data, www.bp.com/productlanding.do?categoryId=6929&contentId=7044622 (last visited Aug. 30, 2009); U.S. Bureau of Economic Analysis, National Economic Accounts, Gross Domestic Product, www.bea.gov/national/xls/gdplev.xls (last visited Aug. 30, 2009).

15. DOE, EIA, *Petroleum Chronology of Events 1970-2000* (2002), *available at* www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/chronology/petroleumchronology2000.htm.

16. DOE, EIA, *Report on Alaska Prudhoe Bay Crude Oil Shut-In* (Aug. 2006), *available at* tonto.eia.doe.gov/oog/special/eia_sr_alaska.html.

17. *Id*.

18. Jamal Saghir, *Upstream Oil and Gas: Securing Supply*, at 2 (2008) (background paper for the Energy Dialogue to Respond to the Global Challenges, 11th International Energy Forum, April 20-22, 2008), *available at* http://sitesources.worldbank.org/intogmc/resources/saghir_securing_supply_background.pdf.

19. According to the IEA, most of the world's current fleet of roughly 600 offshore oil and gas rigs were built between 1970 and 1985 as a result of high demand and high prices. In the 12 years after global oil prices collapsed in 1985, just 40 offshore vessels were constructed. IEA, *World Energy Outlook 2008*, at 320 (2008) *available at* http://www.worldenergyoutlook.org/2008.asp [hereinafter, *World Energy Outlook*].

20. *Annual Energy Review 2008*, *supra* note 18, at 315 (2008).

21. *Drowning in Oil*, at 19, THE ECONOMIST, March 4, 1999, *available at* http://www.economist.com/opinion/displaystory.cfm?story_id=188131.

22. Dr Nimat B. Abu Al-Soof, slide presentation at Offshore Technology Conference 2007, *The Role of OPEC Spare Capacity*, at slide 2, (2007), *available at* http://www.opec.org/opecna/Speeches/2007/attachments/OPEC%20Spare%20Capacity.pdf.

23. Oak Ridge Nat'l Lab., *Transportation Energy Data Book 2008*, at 3-5 (2008), *available at* http://cta.ornl.gov/data/chapter3.shtml (hyperlink "U.S. Cars and Trucks in Use, 1970-2007").

Today, the U.S. economy is dangerously exposed to a global oil market whose fundamental characteristics will ensure that, at least through the medium- term, it is likely to be increasingly volatile and unstable. Growing demand for oil from the developing world, limited access to the reserves owned by national oil companies, the higher cost of production of those fields that are available to international oil companies, and the inevitable fact that at some point in the future, production of conventional oil will peak and be replaced by more expensive unconventional oil, all suggest that the threat posed to our economy by our dependence on oil will continue to grow over time.

In the five years from 2004 to 2008, U.S. oil consumption averaged 20.46 million barrels per day (mbd).[24] In 2008, total transportation was responsible for sixty-nine percent of oil consumption,[25] with light-duty vehicles (LDVs) representing 8.6 mbd of that demand.[26] The transportation sector as a whole is today ninety-five percent reliant on petroleum products for delivered energy[27]—with no substitutes available at scale. This extraordinary reliance on a single fuel to power an indispensable sector of our economy has exposed the United States to a significant vulnerability, both for our economy and for our national security.

II. THE EFFECTS OF OIL DEPENDENCE

A. <u>A Different Kind of Price Spike</u>

If the oil price spike of 2008 felt different from prior episodes of oil market volatility, it was for good reason. When oil prices reached their inflation adjusted all-time high of more than $147 per barrel,[28] it was not just a bump in the road. A portion of that price was, instead, largely the result of a set of fundamental factors that increasingly appear inherent to the global oil market: rising demand for energy in developing countries, stagnant growth in OPEC oil production capacity, and increasingly complex and costly development outside of OPEC.

Between 2003 and 2008, oil prices climbed steadily higher. Economic growth in developing countries like China and India added a new component to the world oil demand picture.[29] In total, world demand for oil increased by eleven percent between 2000 and 2008, but fully 100 percent of this growth occurred in non-Organisation for Economic Co-Operation and Development (OECD) countries.[30]

At the same time that demand was increasing, new oil supplies struggled to keep pace. Within OPEC, decades of underinvestment left total production capacity in 2008 at 34 mbd, less than its 37 mbd level in 1973,[31] despite the fact that the cartel's proved reserves more than doubled between 1980 and 2008.[32] Outside of OPEC, oil supplies also struggled to grow, but for

24. BP Statistical Review of World Energy 2009, *supra* note 2, at 11.

25. *Annual Energy Review 2008*, *supra* note 18, at v.

26. *Annual Energy Outlook 2009.*

27. *Annual Energy Review 2008*, *supra* note 18, at v.

28. Rebecca Kebede, *Oil Hits Record Above $147*, REUTERS, July 11, 2008, *available at* www.reuters.com/article/topNews/idUST14048520080711.

29. Robert Pirog, *World Oil Demand and its Effect on Oil Prices*, at 8, 16, 17, 20, CONGRESSIONAL RESEARCH SERV. (2005), *available at* http://www.fas.org/sgp/crs/misc/RL32530.pdf.

30. BP Statistical Review of World Energy 2009, *supra* note 2, at 11.

31. M.A. Adelman, *Prospects for OPEC Capacity*, 23 ENERGY POLICY 3, 235-241 (1995), *available at* http://www.sciencedirect.com/science/article/b6v2w-3ycmtvc-36/2/06684dc518bcd65fe97dab107292e7fe; IEA, *Medium-Term Oil Market Report*, at 58 (June 2009), *available at* http://www.iea.org/textbase/speech/2009/Fyfe_mtomr2009_launch.pdf.

32. BP Statistical Review of World Energy 2009, Historical Data, Workbook, *Oil—Proved Reserves History*, *available at* www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2009_downloads/statistical_review_of_world_energy_full_report_2009.xls.

different reasons. In United States, the United Kingdom, and Norway, new supplies became more geologically difficult and costly to access. In other high-potential regions like the Caspian Sea area, Latin America, and West Africa, geopolitical factors combined to stymie investment.[33]

As a result of these factors, the global oil market operated with minimal spare capacity—less than three percent of daily demand—throughout most of the period from 2005 to 2008.[34] In such a tight market, even small events around the world can have dramatic effects on oil prices

In 2003, real oil prices averaged $33.75 per barrel.[35] It then rose to $75.14 in 2007 and $97.26 in 2008.[36] By July 2008, oil prices reached a level that was simply unsustainable—the point of demand destruction. Demand for oil is highly inelastic, but only to a point. As gasoline prices soared past $4.00 per gallon, household budgets fell apart.[37] Exacerbated by recession, in the third quarter of 2008, oil consumption was down more than 8.5 percent compared to the same period in 2007, the largest annual decline since the first quarter of 1980.[38]

And yet, despite the current economic environment, the underlying factors that led to record oil prices in 2008 have not substantially altered. Demand growth for oil products—particularly in the industrialized world—has temporarily subsided, to be sure.[39] But this reduction is not the result of any fundamental change in technology, policy, or infrastructure. Rather, it is simply the result of reduced economic activity during the current downturn. As economic activity resumes, demand for all energy—including petroleum—will also increase, particularly in emerging economies that will continue to require high rates of economic growth to accommodate population growth and higher standards of living. Assuming no changes in government policies, by 2030, the International Energy Agency (IEA) expects that world demand for petroleum will increase by 21.2 mbd, or roughly twenty-five percent compared to 2007 levels.[40] Fully 100 percent of the growth is forecast to occur in the developing world, with sixty-three percent in China and India alone.[41]

On the supply side, the picture is also bleak. In its 2008 World Energy Outlook, the IEA conducted a field-by-field analysis of 798 of the world's largest oil fields, which collectively account for three-quarters of all initial reserves ever discovered. Of these initial reserves of 1,306 billion barrels, only 697 billion barrels remain. This latter figure, however, makes up seventy-nine percent of remaining conventional oil reserves. Five-hundred and eighty of the 798

33. *See, e.g.,* IEA, Working Paper Series, *Perspectives on Caspian Oil and Gas Development* (Dec. 2008), *available at* www.iea.org/textbase/papers/2008/caspian_perspectives.pdf.

34. Spare production capacity is defined by the IEA as idle oil production capacity that could reasonably be brought online within 30 days. IEA, *Oil Market Report,* at 18 (Aug. 12, 2009), *available at* http://omrpublic.iea.org/currentissues/full.pdf. During normal market conditions, all spare capacity resides within OPEC member states. Spare capacity can alternatively be thought of as that amount of sustainable production capacity that exists in excess of OPEC's production quota at any point in time.

35. BP Statistical Review of World Energy 2009, Historical Data, *supra* note 39.

36. *Id.*

37. *See, e.g.*, Jad Mouawad, *Gas Prices Soar, Posing a Threat to Family Budget,* N.Y. TIMES, Feb. 27, 2008, *available at* http://www.nytimes.com/2008/02/27/business/27gas.html; Rock Newman, *The Repercussions of $4 Gas*, USNEWS.COM, Mar. 7, 2008, *available at* www.usnews.com/blogs/flowchart/2008/03/07/the-repercussions-of-4-gas.html; Richard S. Chang, *Fueling 1,000 Stories*, N.Y TIMES, June 27, 2008, *available at* wheels.blogs.nytimes.com/2008/06/27/fueling-1000-stories/?scp=30&sq=gas%20prices%20%244%20budget&st=cse; John Branch, *At Small Tracks, High Fuel Prices Put Racers in a Pinch*, N.Y. TIMES, June 3, 2008, *available at* http://www.nytimes.com/2008/06/03/sports/othersports/03fuel.html.

38. DOE, EIA, Petroleum Navigator, *U.S. Product Supplied of Crude Oil and Petroleum Products, available at* tonto.eia.doe.gov/dnav/pet/hist/mttupus2m.htm (last visited Aug. 25, 2009).

39. *Annual Energy Review 2008*, *supra* note 18, at 152-57 (2009), *available at* http://www.eia.doe.gov/emeu/aer/pdf/aer.pdf.

40. *World Energy Outlook*, *supra* note 22, at 93 (2008).

41. *Id.* at 97.

fields are post-peak production and declining at a rate of 5.1 percent per year.[42] In total, the IEA estimated that crude oil output from existing fields will decline from roughly 70 mbd in 2007 to just 27 mbd in 2030.[43] In other words, the world's oil producers will need to add 64 mbd of *new* capacity (including unconventional fuels, biofuels, and natural gas liquids) between 2007 and 2030 to replace lost reserves and meet incremental demand growth from emerging markets.[44]

All told, the IEA estimated that total upstream investment of at least $5 trillion is required to meet oil demand over the next twenty years,[45] a level of investment that seems challenging for national oil companies, whose governments use production revenue to finance other government programs and for international oil companies, which cannot access the most promising reserves and whose remaining reserves are increasingly costly to produce. Moreover, financing has been difficult to attract through the recent recession. In 2009, the IEA estimated that 6.2 mbd of planned capacity additions had either been cancelled or postponed for more than 18 months.[46]

These circumstances paint a picture in which world demand grows and supplies are constricted, and medium-term and long-term oil prices rise until meaningful substitutes are deployed. More importantly, prices can be expected to retain a substantial level of volatility as uncontrollable events around the world continue to rattle markets. Given U.S. dependence on petroleum, this volatility can be expected to exact a heavy toll on long run economic growth. To understand why, it is useful to examine the economic effects of oil dependence in greater detail.

B. The Characteristics of Oil That Underlie Its Economic Power

The volatility of oil prices is the primary manner in which our dependence on oil threatens our economic and national security. Yet, if the price volatility occurred alone, it would not represent a more significant threat than that that posed by our use of any other commodity. Instead, it is the combination of price volatility with three other characteristics that make our petroleum dependence unique: the volume of oil that we consume, the value of oil that we consume in any given time period, and the inelasticity of short-term demand for oil.

1. Volume of Oil Consumed

The United States consumed 19.5 mbd of oil in 2008,[47] twenty-three percent of global consumption.[48] As seen in Figure 1, for at least the past twenty-five years, the demand for oil has generally risen at a relatively steady rate, although it has fallen on a few occasions in response to sustained periods of high prices and recession. It is possible that this long-term trend may change. The small decline in demand that resulted from the recent recession, followed by stagnant demand as tightened fuel economy standards that were enacted in 2007 begin to affect average fuel economy in 2011, may mean that U.S. oil demand is finally nearing a peak.[49] Nevertheless, we will still consume an enormous volume of oil.

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42. According to the IEA, the average size of the fields analyzed was substantially larger than the global average, as the IEA data set includes all super-giant fields and the majority of the giant fields. Because decline rates tend to be lower in larger fields, IEA assumes that the global data set (which would include a much larger share of smaller fields) has a significantly higher average decline rate. IEA calculates this figure to be 6.7 percent. *Id.* at 43.

43. *Id.* at 255.

44. *Id.* at 250, 255.

45. *Id.* at 323, 324.

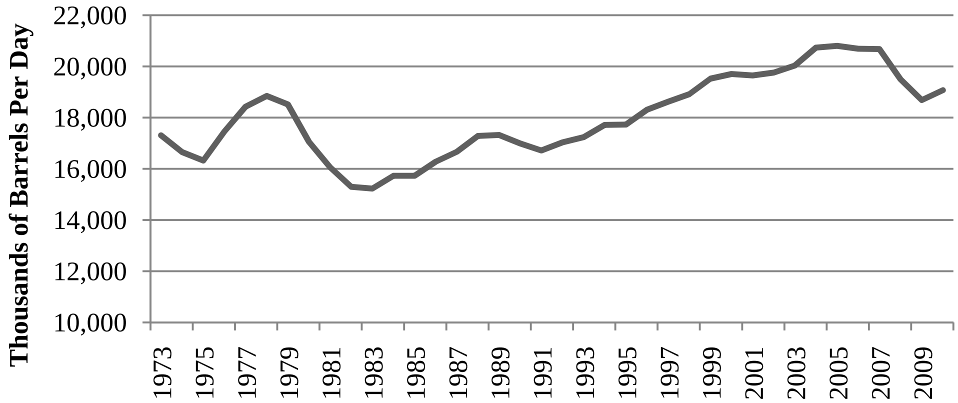
46. IEA, *Impact of the Financial and Economic Crisis on Global Energy Investment*, at 3 (May 24-25 2009) (Background paper for the G8 Energy Ministerial Meeting), *available at* www.iea.org/Textbase/Papers/2009/G8_investment_ExecSum.pdf.

47. DOE, EIA, International Petroleum Monthly, *World Oil Balance, 2005-2009*, Tbl 2.1 (July 2009), *available at* www.eia.doe.gov/emeu/ipsr/t21.xls.

48. *Id.*

49. Energy Independence and Security Act (EISA), Pub. L. No. 110-140, 121 Stat. 1492 at § 102(b)(1)(A) (2007).

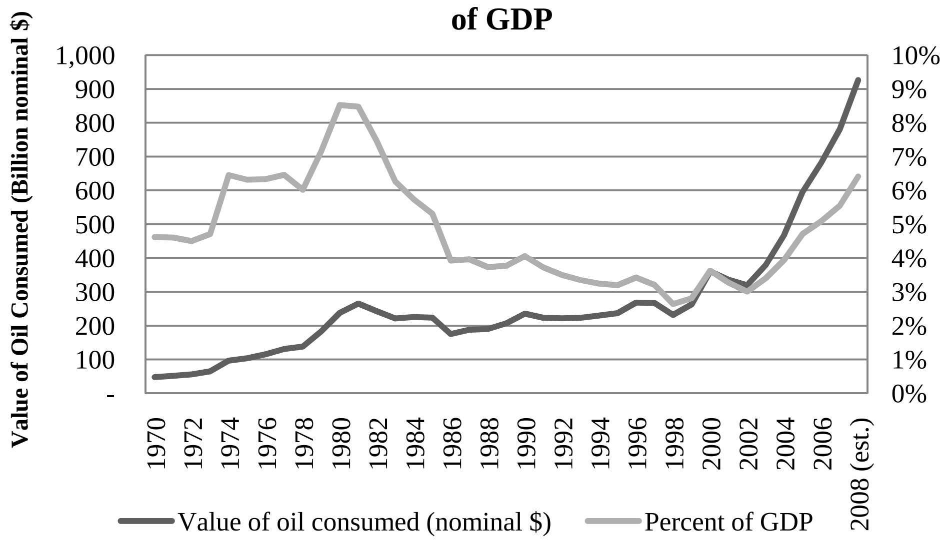
Figure 1: U.S. Petroleum Demand 1973-2010 (1st Qtr.)



2. Value of Oil Consumed

The volume of oil that we consume might not be important in its own right except that oil is relatively expensive. The total value of oil consumed by the United States represents a significant portion of all economic activity in the nation. Even when oil prices are low, the value of our total consumption remains large. As seen in Figure 2, the value of oil and oil products consumed in the United States has ranged from $48 billion to $925 billion over the past three decades, representing between 2.6 and 8.5 percent of the GDP.[50]

Figure 2: Value of Annual Oil Consumption and Percent of GDP



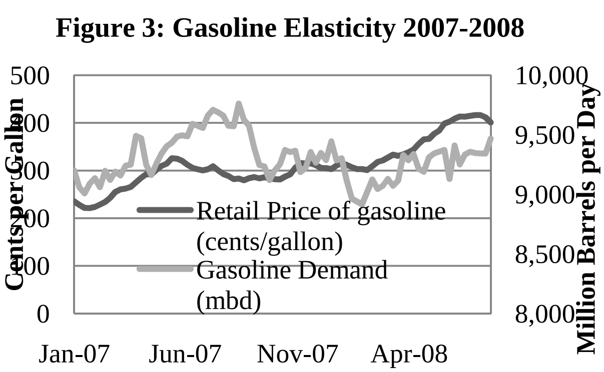
50. *Annual Energy Review 2008*, *supra* note 18, at 77 (2009); BEA, National Economic Accounts, *available at* www.bea.gov/national/index.htm#gdp (last visited Sept. 15 2009).

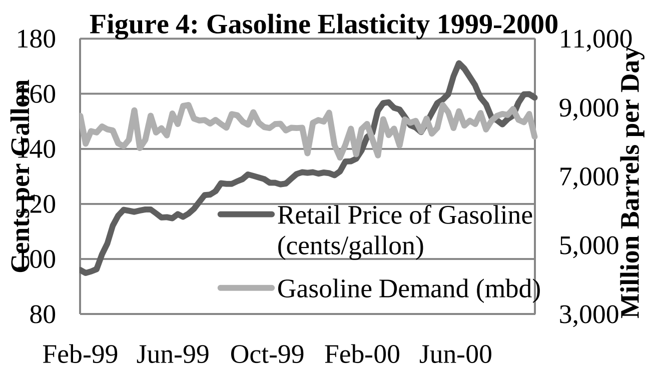
3. Inelasticity of Short-term Demand

Demand for gasoline is highly inelastic in the short-term. There are few (if any) substitutes for oil, at least and especially in the short-term and most consumers cannot stop using gasoline on short notice in response to rising prices. As damaging as such a price increase might be, the costs of alternatives are generally greater, especially if the price spike is perceived to be transient, a perception that nearly always exists and has, thus far, always proven correct.

Our intuitive understanding that the short-term demand for oil is relatively inelastic is confirmed by economic data. The short-term inelasticity of demand can be seen in Figures 3 and 4. Although demand for oil has responded to changes in price, the response is weak. As depicted in Figure 3, from January 2007 through July 2008, the price of gasoline rose from $2.38 per gallon to $4.17 per gallon.[51] Yet during this time period, gasoline demand actually increased by 1.6 percent.[52] Similarly, as depicted in Figure 4, from mid-February 1999 through September 2000 the price of gasoline rose from $0.96 to $1.58 per gallon.[53] Yet during that time period, gasoline demand remained essentially flat, averaging about 8.5 mbd.[54]

These particular examples are supported by research at the Institute of Transportation Studies, University of California, Davis, which examined the short-term price and income elasticity of gasoline demand between 2001 and 2006. The researchers concluded that short-term demand was highly inelastic between 2001 and 2006, with the price elasticity of gasoline demand ranging from -0.034 to -0.077.[55]





4. Oil Price Volatility

We intuitively know that the price of gasoline, the major component of which is the price of oil,[56] is highly volatile, as we have all seen the price of gasoline move sharply higher and sharply lower many times in recent years. Our intuition is supported by the facts, as demonstrated in Figures 5, 6, and 7 below. Figure 5 shows the percent change in the price of oil over the previous month. Since 1974, the average price of oil has either risen or fallen by more

51. DOE, EIA, Petroleum Navigator, *Weekly U.S. All Grades, All Formulations Retail Gasoline Prices*, *available at* http://tonto.eia.doe.gov/dnav/pet/pet_sum_top.asp, (last visited Aug. 28, 2009) [hereinafter, *Petroleum Navigator*].

52. DOE, EIA, Petroleum Navigator, *Weekly U.S. Finished Motor Gasoline Product Supplied, available at* tonto.eia.doe.gov/dnav/pet/hist/wgfupus2w.htm, (last visited Aug. 28, 2009.

53. *Petroleum Navigator, supra* note 72.

54. *Id.*

55. Jonathan Hughes, et al., *Evidence of a Shift in the Short-Run Price Elasticity of Gasoline Demand (*Feb. 14, 2007), *available at* www.econ.ucdavis.edu/faculty/knittel/papers/gas_demand_083006.pdf.

56. This is certainly the case in the United States, but varies by region. In most of Europe for example, government taxes represent the largest component of retail gasoline prices, which contributes to lower overall gasoline price volatility.

than ten percent from the previous month fifty-four times,[57] while over that same time period, the consumer price index has never risen or fallen by more than 1.9 percent in a month (and has only risen or fallen by more than 1.5 percent in a month only once).[58] Oil prices, then, are highly volatile relative to the economy overall. Figure 6 describes the percent change in the price of gasoline from week to week, showing that the price of gasoline has become increasingly volatile in recent years. That is further demonstrated in Figure 7, which plots the difference between the high and low price of gasoline over the previous fifty-two weeks.[59] In fact, one recent study concluded that crude oil prices are currently more volatile than about sixty-five percent of other commodities, and more than ninety-five percent of products sold in the U.S. economy.[60]

Figure 5: Percent Change in Oil Prices and CPI-U From Previous Month

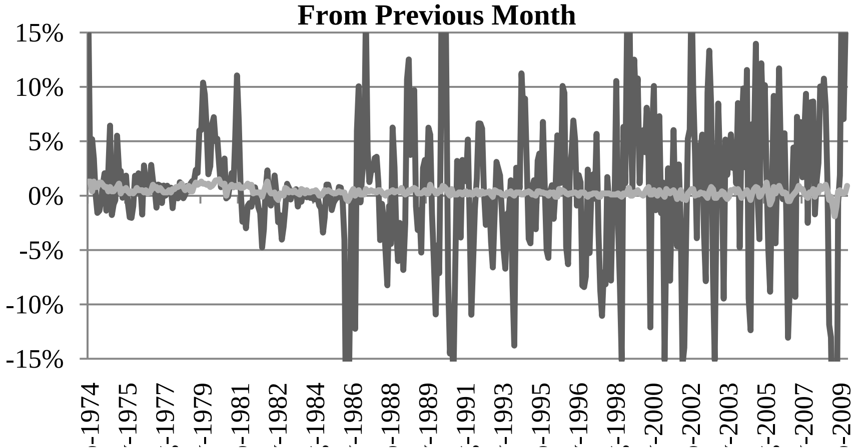
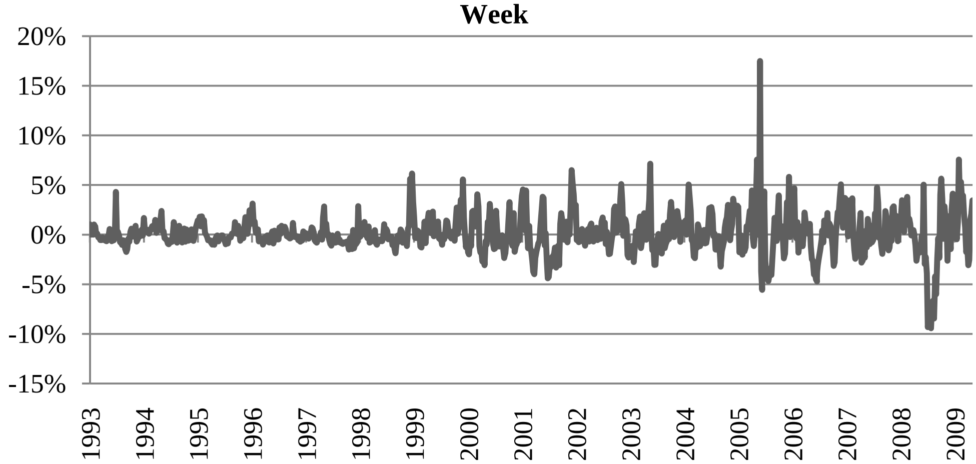


Figure 6: Percent Change in Price of Gasoline From Previous Week



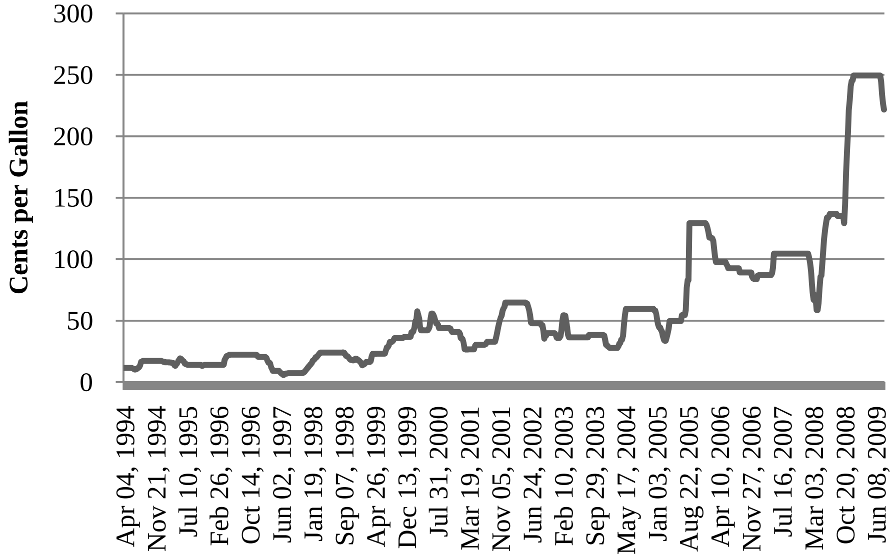
57. *See* United States Dep't of Labor, Bureau of Labor Statistics, *Consumer Price Index Databases*, www.bls.gov/cpi/data.htm (last visited Sept. 15, 2009).

58. *Id.* (Authors' calculation based on data available at United States Department of Labor, Bureau of Labor Statistics, Consumer Price Index Databases).

59. DOE, EIA, *U.S. Gasoline and Diesel Retail Prices*, *available at* tonto.eia.doe.gov/dnav/pet/xls/PET_PRI_GND_DCUS_NUS_W.xls.

60. Eva Regnier, *Oil and Energy Price Volatility*, 29 Energy Economics 3, 405-427 (2007). *See also* Amanda Logan & Christian E. Weller, *Signals on the Fritz: Energy Price Volatility Impedes Investment by Creating Uncertainty*, CENTER FOR AMERICAN PROGRESS (June 2009), *available at* http://www.americanprogress.org/issues/2009/06/energy_price_volatility.html.

Figure 7: Difference Between Min and Max Gas Price Over Previous 52 Weeks



5. <u>All Characteristics Are Equal, But Some Are More Equal Than Others</u>

It is the unique combination of these four characteristics of our use of oil and the world oil market that creates economic vulnerability. If any three characteristics existed without the fourth, then our vulnerability would be significantly reduced or perhaps eliminated. But though our dependence is a function of all four of these characteristics, price volatility is a particularly damaging characteristic because it thwarts the possibility of a sustainable, market-driven effort to use oil more efficiently throughout our economy.

If we could predict future oil prices, and knew that they would simply be higher, we could mitigate much of the damage through planning. In fact, not only can we not predict future oil prices with any degree of accuracy, the one thing that experience has shown in the past is that prices are highly volatile and that at some point after the prices rise sharply, they will fall almost as far as they rose—if not further. Therefore, not only do volatile prices hurt us when prices rise by eroding our purchasing power, but they also harm us when prices fall, by undermining our ability to make investments in efficiency and other alternatives.

Accordingly, a year-long oil price spike is sufficient to do significant economic harm, but is insufficient to induce significant investment in efficiency and alternatives. The lack of such investments then increases the likelihood of further price volatility and its attendant economic harm. In other words, price volatility appears to have, thus far, condemned us to a world in which we are subject to a cycle of oil-driven economic boom and bust.

Moreover, price volatility is, perhaps, oil’s most overlooked characteristic. In fact, changes in price are more harmful than high prices because while one can adjust to a high price, it is hard to adjust to a volatile one. Nevertheless, the combination of these four characteristics, which do not exist anywhere else in the economy, makes oil like nothing else we consume.

C. The Economic Consequences of Our Dependence on Oil

There are at least three mechanisms through which U.S. oil dependence weakens our economy: the economic adjustment costs that result in misallocated resources and reduced GDP, the transfer of wealth to foreigners, and additional means of foregone GDP.[61]

1. Economic Adjustment Costs and Loss of GDP

Economic adjustment costs are the additional reductions of GDP, beyond that which would occur simply as a result of higher prices, which are caused by the temporary misallocation of resources as the result of sudden price changes. This is perhaps the most noticeable category of costs that our dependence on oil imposes on our economy because these accompany price spikes, whereas the other categories discussed below are more likely to exist, though possibly in less potent form, even in the absence of a price spike.

There are at least three categories of economic adjustment costs. First, changes in oil prices alter the budgets of households, businesses and governmental entities, generally resulting in a loss of economic output as the optimal mix of inputs shifts. Second, and closely related to the first category, price spikes can shift consumer demand for products and services, both because consumers may have less disposable income as a result of higher spending on oil and because goods or services may be more expensive if oil (or products derived from oil) was among their inputs. Third, ongoing uncertainty about the future price of oil reduces economic output below what it would be otherwise.

The consumption of gasoline is the primary means through which oil prices filter down to the average American family. American households consume an average of about 1,100 gallons of gasoline each year,[62] at an average cost of $3,597 in 2008,[63] a level of consumption that is, as described above, inelastic, particularly in the short-term. This represents an important part of the 2007 median household's income of $50,233.[64] Each one dollar increase in the annual average price of a gallon of gasoline reduces average American household discretionary spending by about ten percent,[65] effectively acting as a tax increase with the value of the tax accruing to oil producers instead of the U.S. government.[66]

Between 2001 and 2008, the average retail price of gasoline rose from $1.46 to $3.27,[67] increasing the average household's annual gasoline bill by $1,991. By way of comparison, all changes to the federal tax code during that same period decreased annual federal income and

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61. David L. Greene & Sanjana Ahmad, Oak Ridge Nat'l Lab., *Costs of U.S. Oil Dependence: 2005 Update* (Jan. 2005), *available at* http://cta.ornl.gov/cta/publications/reports/ornl_tm2005_45.pdf.

62. DOE, EIA, *Household Vehicles Energy Use: Latest Data & Trends 2001*, at 57 (2005), *available at* www.eia.doe.gov/emeu/rtecs/nhts_survey/2001/tablefiles/es0464(2005).pdf (This estimate for travel in 2001 was published in 2005).

63. Authors' calculation based on data from DOE, EIA, *Annual Energy Review 2008*, at 181 (2009).

64. Press Release, Dep't of Commerce, United States Census Bureau, Household Income Rises, Poverty Rate Unchanged, Number of Uninsured Down (Aug. 26, 2008), http://www.census.gov/Press-Release/www/releases/archives/income_wealth/012528.html.

65. Scott Crawford, *Cutting Back on Discretionary Spending* (2009), *available at* www.debtgoal.com/blog/cutting-back-on-discretionary-spending, (last visited Sept. 15, 2009) (calculation based on data drawn from the United States Department of Labor, Bureau of Labor Statistics 2006 Consumer Expenditure Survey).

66. Of the 8.4 million households that used fuel oil, average consumption was 663 gallons per year for space heating and 228 gallons per year for heating water at an average cost of $2,870 in 2008, imposing on them burdens similar to their consumption of gasoline. (Based on authors' calculations based on data supplied by EIA, *2005 Residential Energy Consumption Survey*, at Tbls US2, SH7, WH (Sept. 2008), *available at* www.eia.doe.gov/emeu/recs/recs2005/c&e/detailed_tables2005c&e.html; *Annual Energy Review 2008*, *supra* note 18, at 179).

67. *Annual Energy Review 2008*, *supra* note 18, at 181.

estate taxes by about $1,900 for the median household.[68] In other words, every penny that the typical household saved due to federal income and estate tax cuts was spent on higher gasoline bills. Businesses that consume oil face similar challenges, as rising prices undermine their budgets as well.

Sustained high gasoline prices, which effectively exist through very high tax rates in much of Europe, might cause U.S. families to reorient their lifestyles around reducing fuel expenditures. This has not yet occurred, however, because persistent opposition to increasing the tax on gasoline keeps taxes low, allowing prices to fall as well as rise, and to fall to levels near which most consumers are not concerned about fuel economy. Moreover, the prospect that prices may fall in the future provides a fig leaf that enables households to make economically irrational decisions to favor perceived quality of life over low energy consumption: even if prices are high now, they may fall in the future.

2. Transfer of Wealth

It is easy to understand how our dependence on oil imports constitutes a significant transfer of wealth from U.S. consumers to foreign producers. The value of that transfer is equal to the product of the volume of oil and refined products that the United States imports from foreign producers and the average cost of imports.[69] According to the U.S. Department of Energy, the nation imported $450 billion of petroleum in 2008 alone.[70]

The transfer of wealth abroad directly increases our trade deficit. As oil prices have steadily increased in recent years, petroleum imports have exacted a heavy toll on the nation's current account balance. In 2008 alone, net trade in petroleum and petroleum products cost the American economy $388 billion.[71] [72] This staggering total represented fifty-seven percent of our total trade deficit of $681 billion.[73] Our 2008 petroleum deficit was greater than the deficit with China, NAFTA, or the European Union,[74] and it exceeded the combined 2008 cost of wars in Iraq and Afghanistan.[75]

This transfer of wealth has the potential to reduce our GDP because money spent abroad on oil and petroleum products may not be recycled to be spent on goods and services in the United States. Moreover, to the extent that we cannot finance our imports with exports, we must finance our imports with foreign borrowing, which imposes a drag on the U.S. economy through significant interest charges. The trend of increased imports should be expected to continue as long as domestic oil production continues to decline and oil consumption remains at least at current levels.[76]

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68. Tax Policy Center, Urban Institute and Brookings Inst., *Individual Income and Estate Tax Provision in the 2001-08 Tax Cuts*, at Tbl T08-0147 (2008), *available at* www.taxpolicycenter.org/numbers/displayatab.cfm?DocID=1856&topic2ID=150&topic3ID=157&DocTypeID=2.

69. While it is true that the United States also exports a small amount of refined product, transfer of wealth is intended simply to measure the amount of capital exchanged for fuel.

70. *Annual Energy Review 2008*, *supra* note 18, at 81.

71. Our net trade in petroleum is lower than our gross import of petroleum because although the United States exports little if any crude oil, we do export finished products, largely, but not exclusively, to our Western Hemisphere trading partners.

72. *Annual Energy Review 2008, supra* note 18, at 77.

73. U.S. Dept. of Commerce, Bureau of Economic Analysis, 89 SURVEY OF CURRENT BUSINESS 4, 28, Tbl 1 (Apr. 2009), *available at* www.bea.gov/scb/pdf/2009/04%20April/0409_ita-tables.pdf..

74. *Id*. at 46, 47, 48 Tbl 12.

75. Amy Belasco, *The Cost of Iraq, Afghanistan, and Other Global War on Terror Operations Since 9/11*, CONG. RESEARCH SERV., at 13 (2009), *available at* http://www.fas.org/sgp/crs/natsec/RL33110.pdf.

76. Whereas we have calculated the magnitude of the transfer of wealth based on our use of oil, Greene et al. have calculated the magnitude of the loss based on the exercise of monopoly power by foreign oil producers. Rather than categorize the value of all imports as imposing a cost on our economy by increasing the trade deficit, Greene has calculated the increase in

3. Additional Foregone GDP

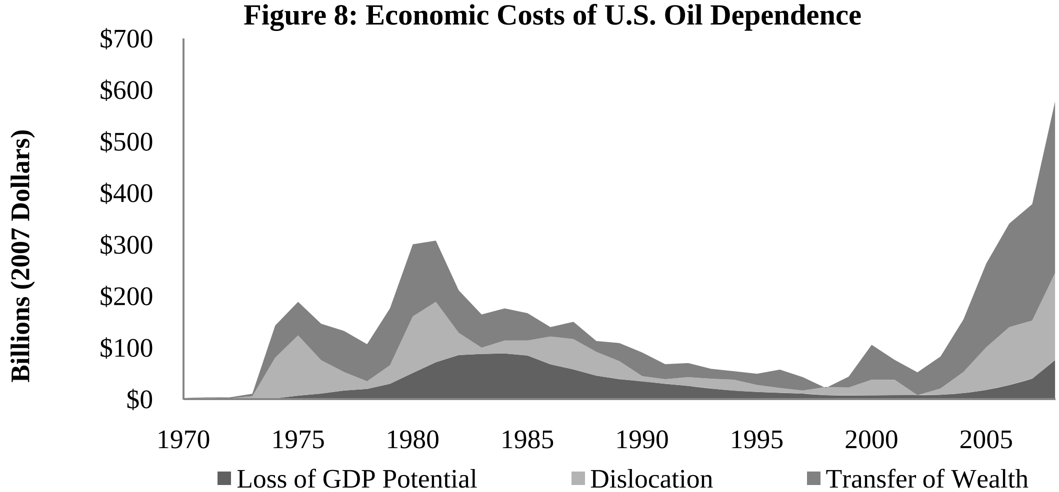
The third category of economic losses that results in additional foregone GDP is the decline in consumer and producer surplus which results from the exercise of monopoly power by oil producers, and the lost consumer and producer surplus in other product markets whose prices have been affected by the price of oil.[77] This loss occurs whenever prices are higher than they would be in a competitive market (an occurrence that can usually be attributed to OPEC action), whether or not they have recently spiked.

When demand for a product is inelastic, consumer surplus is typically larger than it would be if demand were unit elastic or elastic because consumers are willing to pay more for the product that the seller is charging.[78] Oligopolists exploit their power by raising prices to maximize their profits while reducing output, which reduces consumer surplus.[79]

* * *

The magnitude of the costs of oil dependence across these three categories clearly varies over time. When oil prices are steady and low, the economic impact of our dependence on oil is also relatively low. When oil prices are high and volatile, the economic costs are generally high and damaging. According to analysis performed at DOE, the costs to the economy, depicted in Figure 8 below, reached $600 billion in 2008.

Figure 8: Economic Costs of U.S. Oil Dependence



There can be no doubt that the characteristics of our oil consumption and oil markets described above have led to periods in which the loss of GDP was sufficient to throw the economy into recession, with all of its attendant damage. As demonstrated in Figure 9, oil price spikes have either preceded or concurred with every U.S. recession since 1970, including the

our foreign debt resulting from the exercise of monopoly power by oil exporters. He calculates the value of the transfer as the total value of all crude oil and petroleum product imports, as the volume of imports multiplied by the difference between the price of oil and the estimated price of oil in a competitive market and the price of oil in the actual market. It is his methodology that forms the data used in Figure 8 and the accompanying text.

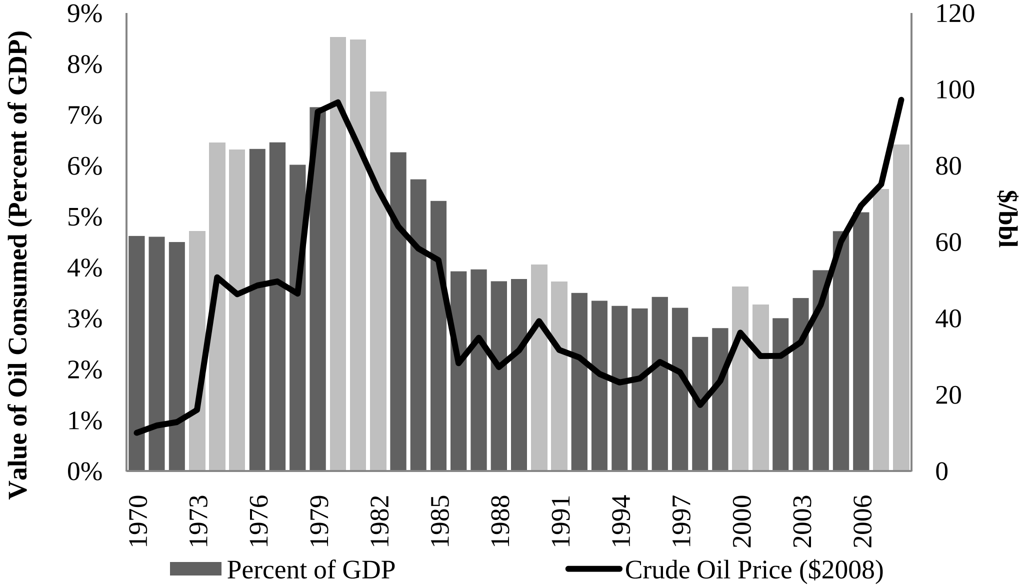
77. *Id.*

78. *Id*. at 78.

79. *Id*. at 197.

recent one. Although there obviously are numerous factors that contributed to the recession, some recent research has concluded that the oil price spike in 2008 caused the recession to begin six to nine months earlier (in December 2007) than would have occurred otherwise.[80] Although the correlation between oil prices and the onset of recessions does not necessarily imply causation, there is a strong negative correlation between oil price spikes and the strength of the economy.[81]

Figure 9: U.S. Oil Expenditures and Economic Recessions



Note: Recessionary periods are in light gray

D. National Security Consequences of Our Dependence on Oil

While the economic costs of U.S. oil dependence are quantifiable, the national security costs are generally not. There are at least two primary consequences of America's heavy reliance on petroleum. The first is that U.S. foreign policy is constrained in dealing with a range of foreign policy priorities in oil-producing countries and regions. Second, and closely related, is that the U.S. military is overburdened and overexposed by our need to maintain secure transit routes for global oil supplies.

1. Foreign Policy

At a general level, one needs to look no farther than the so-called Carter Doctrine to summarize the impact of U.S. oil dependence on our foreign policy. On January 23, 1980, in his State of the Union address to Congress, President Carter declared,

> [l]et our position be absolutely clear: An attempt by any outside force to gain control of the Persian Gulf region will be regarded as an assault on the vital interests of the United States of America, and such an assault will be repelled by any means necessary, including military force.[82]

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80. James D. Hamilton, *Causes and Consequences of the Oil Shock of 2007-08* (Apr. 2009) *available at* dss.ucsd.edu/~jhamilto/Hamilton_oil_shock_08.pdf (Working Paper).

81. *See, e.g.*, REBECA JIMÉNEZ-RODRÍGUEZ & MARCELO SÁNCHEZ, WORKING PAPER SERIES NO. 362 – OIL PRICE SHOCKS EMPIRICAL EVIDENCE FOR SOME OECD COUNTRIES (European Central Bank 2004), *available at* http://cta.ornl.gov/cta/publications/reports/ornl.

82. The State of the Union Address Delivered Before a Joint Session of the Congress, 1 Pub. Papers 114 (Jan. 23, 1980).

Of course, the United States may have had a number of reasons for intervening in any invasion of Middle East countries. The Carter Doctrine was largely directed at the Soviet Union in response to its invasion of Afghanistan. Yet, adventurism in the heart of the Persian Gulf had a special significance because of American dependence on a stable global oil market. Our willingness to respond "by any means necessary" might not have held true in many other places.

The statements and policies of successive administrations confirm this notion. President Reagan extended the Carter Doctrine to cover not just external but regional threats to Persian Gulf oil supplies.[83] In his corollary to the Carter Doctrine, he stated "there is no way that we could stand by and see [Saudi Arabia] taken over by anyone that would shut off [the] oil."[84] And in 1989, National Security Directive (NSD) 26, issued by President Bush, stated

> [a]ccess to Persian Gulf oil and the security of key friendly states in the area are vital to U.S. national security. The United States remains committed to defend its vital interests in the region, if necessary and appropriate through the use of U.S. military force, against the Soviet Union or any other regional power with interests inimical to our own.[85]

More recently, the National Defense Strategy issued by Secretary of Defense Robert Gates in June 2008 notes that

> [t]he United States requires freedom of action in the global commons and strategic access to important regions of the world to meet our national security needs. The well-being of the global economy is contingent on ready access to energy resources. . . . The United States will continue to foster access to and flow of energy resources vital to the world economy.[86]

Today, for instance, our interest in stable oil markets constrains our flexibility in dealing with a range of threats pose by Iran. U.S. sanctions may rank among the top factors preventing Iran from maximizing its oil production potential. Yet, the United States' option set in dealing with Iran's efforts to develop nuclear weapons, its continued support of Hizb'allah in Lebanon, and its decidedly unhelpful role in Iraq is likely sharply limited by Iran's important role in the global oil market. Iran is only one of many examples across the world of the manner in which our oil dependence has constrained our conduct of foreign policy. This and many other foreign and military challenges are born at least in part out of our need for a steady global supply of oil.

2. <u>The World's (Oil) Police</u>

In a world dependant on oil, the United States has periodically endured a unique burden as the guarantor of the world's oil supplies. At least two large-scale military actions, Operation Desert Storm and Operation Iraqi Freedom, are frequently regarded as having been tied to protecting oil flows. Though some have tried, we believe that it is impossible to quantify the military burden associated with oil dependence.[87] In our view, however, it is simply impossible to quantify the American response to the Iraqi invasion of Kuwait based on oil dependence versus other *causus belli*, such as defense of Kuwaiti sovereignty. It is similarly imprecise to assign the full cost of Operation Iraqi Freedom to oil dependence versus, for example, democracy building. No doubt, oil dependence and oil politics played a strong role in both actions, but assigning a precise monetary cost seems an exercise in futility.

In addition to large scale deployments, other, more routine U.S. military activities occur on an ongoing basis that are also closely associated with energy security and protecting oil flows.

83. KEITH CRANE, ANDREAS GOLDTHAU, ET AL., IMPORTED OIL AND U.S. NATIONAL SECURITY 61 (RAND 2009).

84. The President's News Conference, 1 Pub. Papers 873 (Oct. 1, 1981).

85. George H.W. Bush, National Security Directive 26, at 1 (Oct. 2, 1989) *available at* www.fas.org/irp/offdocs/nsd/nsd26.pdf.

86. Crane, *supra* note 117, at 62.

87. ANITA DANCS, *ET. AL.*, *THE MILITARY COSTS OF SECURING ENERGY* 4 (National Priorities Project 2008), *available at* www.nationalpriorities.org/auxiliary/energy_security/full_report.pdf; KEITH CRANE, ET. AL., IMPORTED OIL AND U.S. NATIONAL SECURITY 59-74 (Rand 2009), *available at* www.rand.org/pubs/monographs/2009/RAND_MG838.pdf.

For example, U.S. naval assets routinely patrol key shipping chokepoints, including the Straits of Malacca in the Far East, and American forces are currently training security forces to guard critical energy infrastructure in the South Caucasus, West Africa, and the Middle East—almost exclusively at the expense of the U.S. taxpayer. These kinds of routine security functions are often explicitly tied to the preservation of shipping lanes for oil and other goods. More broadly, providing general security training is often aimed at improving the overall security and stability of a region, which is a prerequisite for expanded and secure oil production. Ultimately, the U.S. military helps to provide long-term security—which is a prerequisite for oil production—and oil is a factor in choosing where it should focus on providing that security.

III. OPERATING WITHIN THE EXISTING PROGRAM

U.S. oil dependence overburdens our military while undermining both our economic stability and our foreign policy priorities. So long as we fail to address this vulnerability we will continue to risk the continuance of an oil-driven boom and bust economic cycle. High prices will weaken our economy and initiate economic slowdowns which cost us jobs and undermine our standard of living, while volatility undermines the incentive to engage in efforts to reduce our dependence on oil, thus continuing the cycle. In addition to weakening our economy, it will continue to undermine our foreign policy and impose significant burdens on our military, including the need to put American lives in harm's way, a cost that is intolerable.

The challenge we face is how best to break this dependence while ensuring that the U.S. economy retains the mobility and flexibility it needs in order to grow.

This is not necessarily a new question. Since the 1970s, Congress has established the Department of Energy[88] and passed a slew of legislation to enhance our energy and economic security. This legislation has provided assistance to a wide range of technologies to fuel vehicles, including synthetic fuels,[89] natural gas,[90] biofuels,[91] hydrogen,[92] and electricity.[93] The range of assistance, however, is not the result of a national energy policy to determine the best and most efficient outcome, but instead is the product of a haphazard, politicized, and inconsistent approach, with policymakers at times unwilling to interfere with industry and at other times mandating or subsidizing various technologies. The former is problematic because it has meant that the market has not been consistently required to incorporate the cost of the externalities of oil dependence. The latter is problematic primarily because support for technology has been highly politicized, with subsidies, mandates, and demonstration projects starting and ending based on factors other than the viability or deployment of the technology.

The fact is that we have had no discernable long-term national energy strategy. It is perhaps ironic that the challenge of transforming our energy sector is compared to the Apollo project. The Apollo project had a clearly defined goal: to send a man to the moon and bring him safely back to earth by the end of the 1960s. Our energy policies, however, are not similarly focused, or even focused at all. We do a little of many things—such as biofuels, natural gas vehicles, hydrogen vehicles, electric vehicles, and more efficient gasoline vehicles—without a clearly focused commitment to achieve any positively stated goal. The result is mixed messaging to the industrial sector, producing little or no progress.

88. Department of Energy Organization Act , Pub. L. No. 95-91, 91 Stat. 565 (1977).
89. *See, e.g.*, ESA80, *supra* note 156, at §§ 100-95.
90. *See, e.g.*, EPA92, *supra* note 157, at §§ 201-514, 1913; 26 U.S.C. § 179A (2006).
91. *See, e.g.*, ESA80, *supra* note 156, at §§ 201-514; 26 U.S.C. § 30C (2006).
92. *See, e.g.*, EPA92, *supra* note 157, at §§ 201-514, 1913; 26 U.S.C. §§ 30C, 40A, 179A (2006).
93. *See, e.g.*, *Id.* at §§ 201-514, 1913; 26 U.S.C. §§ 30B, 30C (2006).

Significant oil consumption reduction must come from the transportation sector, which is responsible for more than seventy percent of American oil demand. Moreover, the approach of most policymakers to date—increase domestic supply of oil, reduce demand—while laudable and necessary, will never provide true security for the U.S. economy.

A. Domestic Oil Production

Increasing domestic oil production can improve the U.S. trade deficit, reduce the magnitude of the wealth transfer, and increase reinvestment of oil revenue into the United States. Increased supply cannot, however, meaningfully reduce oil price volatility or the economic damage that volatility wreaks on U.S. households and businesses. If for no other reason, this is true simply because the United States does not possess enough oil to meaningfully alter the global supply-demand balance.

The Department of Energy currently forecasts U.S. crude oil production to be 5.79 mbd in 2020 and 7.14 mbd in 2030.[94] This rise of just 1.35 mbd is itself highly questionable given the steady decline in U.S. crude oil output over the past thirty years. Moreover, the entire forecasted increase derives from fields in the lower forty-eight contiguous states, which leads us to believe that DOE has assumed new production from the Atlantic and Pacific offshore regions, which is highly speculative in nature.[95]

Leaving aside domestic production potential, the basic characteristics of the global oil market completely undermine the ability of domestic oil production to insulate the U.S. economy from oil price volatility. Though oil is produced, transported, refined, and consumed at all corners of the globe, there is a single world market for oil. All variations from that price represent adjustments to account for the location of the oil and its quality, international variations in demand between regions, and changes in the balance of demand for different oil products. Professional traders quickly arbitrage out any unsupported price differentials.

Price formation in the global oil market implicitly accounts for all of the oil production and all of the oil consumption in the world. All consumers of oil are dependent on all producers of oil to get their supply to market. Often, isolated variances from this process result in dramatic price swings, particularly in times of low spare capacity. For instance, in late 2002 and early 2003, an oil worker strike in Venezuela resulted in a sharp reduction of oil production.[96] The result was not simply higher prices for the United States, which is the main customer for Venezuela's oil; it was instead a higher *global* price for oil.[97] In other worlds, consuming nations are dependent on every supplier in the world—those from whom they purchase and those from whom they do not—to ensure a stable supply and price of oil. Therefore, increasing domestic oil production will not insulate the United States from oil price volatility.

The only means to address volatility directly through supply would be to build sufficient spare production and refining capacity to serve as buffers that could quickly increase or decrease production in response to exogenous events to maintain price stability. The last time that the United States was able to do this was in the 1960s, when the Texas Railroad Commission could meaningfully manage global supply. Today, however, such an undertaking would be impossible.

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94. DOE, EIA, *An Updated Annual Energy Outlook 2009 Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act and Recent Changes in the Economic Outlook*, Apr. 2009, at TbleA.11, *available at* http://www.eia.doe.gov/oiaf/sercierpt/stimulus/pdf/stimulus.pdf.

95. Indeed, in its online supplemental tables, DOE shows crude oil production from the Atlantic and Pacific increasing from roughly 100,000 b/d today to 700,000 b/d by 2030. DOE, EIA, *Annual Outlook 2009 Updated Annual Energy Outlook 2009 Reference Case with ARRA*, Apr. 2009, *available at* www.eia.doe.gov/oiaf/aeo/index.html.

96. IEA, *Oil Market Report*, Jan. 17, 2003, at 17-18, *available at* http://omrpublic.iea.org/omrarchive/17jan03full.pdf.

97. *Id.* at 38.

B. Biofuels

Biofuels are largely produced domestically, a fact that is widely perceived to enhance our security relative to the use of imported oil.[98] Displacing some portion of petroleum derived fuel with domestic biofuels, however, will not substantially improve our energy and economic security. While the source of biofuels amy differ from petroleum products, their use is nearly identical. Thus, a broad expansion of biofuel production, concomitant with the establishment of a policy that all vehicles operate on a wide range of liquid fuels, would essentially convert the domestic gasoline market into a market for liquid motor fuel in which consumers would generally be indifferent to the particular mixture of gasoline and other liquid fuels, so long as price was adjusted to account for the fuel's actual energy content. Once the markets for the two fuels effectively merge, the problems that plague gasoline would also affect biofuels, as the price of domestically-produced biofuels will be a function of the price of gasoline.

The ultimate result is that, from an energy security perspective, domestic production of biofuels is functionally equivalent to domestic production of oil; it improves the U.S. trade deficit, reduces the magnitude of the wealth transfer, and increases investment into the United States, but does not address price volatility.

C. Fuel Efficiency

One of the few meaningful steps we can take to enhance our energy and economic security while continuing to use oil to power our cars is to increase the fuel efficiency of those vehicles, thereby reducing the petroleum intensity of the economy. As mentioned earlier, the petroleum intensity of the U.S. economy fell by forty-five percent between 1973 and 1995, chiefly due to improved fuel economy of passenger cars, the virtual elimination of oil as a fuel for electric power generation, and a shift to less energy-intensive economic sectors for growth. That improvement has reduced the importance of oil in the economy and mitigated some of the effects of higher and volatile oil prices. Yet much of that improvement was achieved prior to 1990 and due to increased automotive efficiency in response to the establishment of Corporate Average Fuel Economy (CAFÉ) standards in 1975.[99] However, between 1987 and 2007, however, fuel economy for America's LDVs remained essentially unchanged.[100]

In December, 2007, Congress passed the Energy Independence and Security Act of 2007 (EISA), which increased fuel-economy standards for the first time in nearly two decades.[101] In May 2009 President Obama announced a tightening of this standard, ultimately requiring an average fuel-economy standard of 35.5 mpg in 2016.[102]

While EISA will result in substantial fuel savings, it does not address the underlying problem represented by our transportation network's nearly complete dependence on oil. Tighter fuel standards can reduce, but not eliminate, the effects of volatility, because new business and

98. Oxford Analytica, *Biofuel Benefits Go Beyond Environment*, FORBES, Apr. 10, 2006, *available at* www.forbes.com/2006/04/07/biofuel-benefit-ethanol-cx_0410oxford.html; DOE, EERE, Alternative Fuels and Advanced Vehicles Data Center (AFAVDC), *Ethanol Benefits*, July 10, 2009, *available at* http://www.afdc.energy.gov/afdc/ethanol/benefits.html.

99. *See* EPCA § 301, codified at 15 U.S.C. §§ 2001-12 (2006).

100. Environmental Protection Agency (EPA), *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2007 – Executive Summary*, at ii (September 2007), *available at* http://www.epa.gov/oms/cert/mpg/fetrends/420s08003.pdf.

101. *See* EISA, *supra* note 70, at § 102; KELLY SIMS GALLAGHER & GUSTAVO COLLANTES, ANALYSIS OF POLICIES TO REDUCE OIL CONSUMPTION AND GREENHOUSE-GAS EMISSIONS FROM THE U.S. TRANSPORTATION SECTOR 4 (Harvard University, Belfer Ctr. for Sci. and Int'l Affairs 2008), *available at* http://belfercenter.ksg.harvard.edu/files/2008_Gallagher_Collantes_AutoPolicyModelingResults.pdf.

102. White House Office of the Press Sec'y, President Obama Announces National Fuel Efficiency Policy (May 19, 2009), http://www.whitehouse.gov/the_press_office/President-Obama-Announces-National-Fuel-Efficiency-Policy.

governmental budgets will assume increased efficiency. Nor would they insulate us from price spikes brought on by, for example, a new military conflict in the Middle East, though they can help by reducing the magnitude of the economic effects of price spikes when they do occur. We have seen, however, that merely reducing the fuel intensity of the economy will not eliminate the effects of high and volatile prices, which can in fact, be quite severe.

IV. TRANSFORMATIONAL CHANGE FOR THE LONG-TERM: ELECTRIFICATION

Working within the traditional paradigms, though helpful, cannot offer the transformative change required to end our nation's dependence on petroleum. What is required is a new model: electrification of our nation's short-haul ground transportation system.

GEVs offer the potential to address the two primary problems that electric vehicles (EVs) have faced in the past. The viability of EVs has long been limited by their range and the time needed to recharge their batteries. By combining an electric motor and gasoline engine into a single drive-train in a hybrid-electric vehicle (HEV), automakers were able to significantly improve gasoline mileage. Now that it is clear that an HEV can be modified to operate as a plug-in hybrid electric vehicle (PHEV), a vehicle that operates in part (or exclusively) as an electric car until its battery reaches its discharge limit, and then as a traditional hybrid until it can be recharged, the possibility of an ultra-efficient car is more attainable than ever before. Because the majority of vehicles travel fewer that forty miles a day, such a vehicle offers the opportunity for much of the oil savings possible from EVs without their restriction on range. The deployment of PHEVs, therefore, represents an opportunity to radically improve the fuel efficiency of the short haul transportation fleet, even prior to the deployment of EVs, reducing the petroleum intensity of the U.S. economy in the short-run. In doing so, they can offer a step towards the deployment of battery EVs, while improving our economic and national security.

Given our relatively recent discovery of the new opportunities provided by GEVs, one can reasonably ask why we should deliberately choose the path of electrification. Given that we have emphasized different approaches to our energy security at different times, including interest in hydrogen, biofuels and the electrification in just the past decade alone, why should we focus our effort, energy and investments in one particular technology that itself remains unproven? Does it not seem likely that five years from now we will believe that some other technology holds more promise than electrification, and that this too was just a phase?

A. Why the Government Should Intervene

Government intervention in the marketplace should generally be limited to those instances in which there is a market failure. There is a clear market failure in the world oil market. OPEC members engage in oligopolistic behavior by withholding oil supplies from the market. OPEC members, as a matter of practice, withhold production from the market despite the fact that their marginal cost of production was far below the market price of oil.[103] Since the short-term demand curve is so inelastic, the revenue they lose by withholding volume may be made up for with higher prices.[104]

103. *See, e.g.*, CBS News, Transcript of 60 Minutes (Dec. 7, 2008), www.scribd.com/doc/8743779/60-Minutes-Transcript-on-Saudi-Arabia-Bullish-Oil-Future-12708, (last visited Sept. 15, 2009).

104. *See, e.g.*, James L. Williams, *Oil Price History and Analysis*, WTRG Economics, www.wtrg.com/prices.htm (last visited Sept. 15, 1009); *See also*, Martin Seiff, *OPEC Oil Price Push May Threaten World* Recovery, UPI, May 28, 2009, *available at* www.upi.com/news/issueoftheday/2009/05/28/OPEC-oil-price-push-may-threaten-world-recovery/UPI-7358124354589/ (For most non-OPEC producers, although the fixed costs of oil production may be very high, the cash costs are quite low, meaning that they always have an incentive to produce at or near maximum capacity. They cannot, therefore, counteract OPEC production cuts. OPEC members have therefore had the ability to exercise oligopoly power over the market even though they controlled less than half of all production).

If OPEC-like behavior were to occur within our borders, the government would intervene. Colluding with competitors to withhold product from the market is a clear violation of U.S. antitrust laws. Those laws, however, do not and cannot apply to sovereign nations. Geopolitical factors, violence, and instability represent additional factors within the global oil market over which the United States has no practical control, but that directly threaten our economy. In the alternative, if we were willing to internalize some of the external costs of oil use through a tax, such as security costs or carbon emissions, consumers might increase their use without additional government intervention. But political leaders are unwillilng to support substantial fuel taxes to internalize such costs.

Unable to address supply, the government is left with no option but to address the demand side of the equation. The policy question is whether the government should take unprecedented measures to address this market failure. We believe that it must for all of the reasons above. Oil's role in the economy is both unique and enormous, and the anticompetitive behavior undertaken by OPEC members significantly damages our national security, our foreign policy, and our economy. A policy that would penalize the oligopolistic behavior might seem the best policy, but even if it were available it would fail to address either the myriad of supply side problems outside of OPEC or the climate change problems associated with petroleum. Moreover, policies undertaken over the past thirty-five years to this point have largely failed. Our conclusion is that the government should adopt a policy to affirmatively promote electrification of the short-haul transportation sector of the economy not because we generally support government intervention in the market, but because, to paraphrase Winston Churchill, doing so may be the worst policy choice available, except for every other one.[105] \

B. Balancing Energy, Economic and National Security

Electrification represents the best opportunity in the foreseeable future to enhance our energy, economic, and national security while reducing our nation's dependence on oil. EVs, which are powered by batteries that are charged by connecting them to the electrical grid either at home, work, or elsewhere, operate without using oil. However, the viability of EVs has been constrained by the high cost of batteries, vehicle range and recharging time.

While we await the development of affordable electric vehicles, the combination of high oil costs, concerns about oil security and availability, and air quality issues related to vehicle emissions are driving interest in "plug-in" PHEVs. PHEVs feature a larger battery and a plug-in charger that allows the driver to charge the battery by connecting it directly to the power grid. When the battery is sufficiently charged, the vehicle may operate in a battery-depleting all-electric or blended mode. Once the battery is depleted to the point that it can no longer power the vehicle, the vehicle may then operate as a traditional HEV, powered by its gasoline-fueled engine and its electric motor, a mode of operation during which it would still generally achieve far greater fuel economy than a gasoline-powered vehicle. Therefore, PHEVs may derive a substantial fraction of their miles from grid-derived electricity, but without the range restrictions of pure battery EVs.

The average LDV's trip is less than ten miles, and average households log less than thirty-five miles per day.[106] According to data assembled by the U.S. Department of Transportation, vehicles driven forty or fewer miles per day log an estimated seventy percent of all vehicle miles traveled on weekdays and eighty percent of all vehicle miles traveled on

105. *See* The Official Report, House of Commons, 444 Parl. Deb., H.C. (5th ser.) (1947) 206-07, *available at* http://hansard.millbanksystems.com/commons/1947/nov/11/parliament-bill.

106. Oak Ridge Nat'l Lab, *supra* note 26, at Figs 8.3, 8.5.

weekends.[107] Because the majority of Americans drive only relatively short distances each day, electric cars should be able to satisfy most driving needs even if they need to recharge more often than gasoline-powered vehicles need to be refueled.

In 2006, the Bush administration announced the U.S. Advanced Energy Initiative, which sought to develop a PHEV capable of traveling up to forty miles on a single electric charge (a PHEV-40).[108] Such a vehicle could cut many drivers' gasoline consumption in half If charged only at home,[109, 110, 111] and as much as 80 percent if the driver had the capability to charge at work and elsewhere.[112] Deployed at scale, this technology would provide significant oil savings, reducing the petroleum intensity of the economy and enhancing our economic and national security. Therefore, while EVs might represent complete freedom from petroleum, PHEVs can constitute a first step towards that goal, a step that will support the development of common infrastructure and technology, and which can, even as an interim step, significantly reduce the petroleum dependence of the U.S. economy. As of early 2010, production of PHEVs is essentially limited to demonstration vehicles and prototypes. But their initial deployment is on the horizon.

A path towards electrification is also supported by the fact that a substantial portion of the LDV fleet could be recharged using the existing electric infrastructure with important, but practical, upgrades.[113] While the grid is generally capable of recharging the first PHEVs to hit the consumer market, as their numbers grow over time, it will be necessary to upgrade the infrastructure. But that investment is both manageable in cost and sound in policy. Most of the upgrades to the grid are either in the last few feet of wire (connecting existing wires to charging devices), or related to technological upgrades to transform the existing grid into a "smart grid," upgrades that will likely occur whether or not GEVs are deployed. Moreover, the transformation will take place over time, creating an opportunity to explore the best way to fund any necessary upgrades, based, at least in part, on the business models that develop to support GEVs.

For the reasons stated above, we believe that the development of PHEVs represents a transformative event that signals the first step towards the wider deployment of a range of GEVs that will have radical implications for energy security. For those drivers who want the benefits of an electric vehicle without restricted range, a PHEV should meet their needs, almost immediately. In doing so, they can represent a cornerstone of our transportation future, one which will strengthen our economy and national security while enhancing our environment.

C. Why Electrification is the Best Approach

Electrifying the light-duty fleet is the best approach to reducing our dependence on oil for five reasons: using electricity promotes fuel diversity; electricity is generated from a domestic portfolio of fuels; electricity prices are less volatile than oil and gasoline prices; using electricity

107. *Id.*

108. DOE, EERE, *Plug-In Hybrid Electric Vehicle R&D Plan*, at 1, 4, 5, 7 (2007), *available at* http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/phev_rd_plan_02-28-07.pdf.

109. ELECTRIC POWER RESEARCH INSTITUTE (EPRI), COMPARING THE BENEFITS AND IMPACT OF HYBRID ELECTRIC VEHICLE OPTIONS, at 2-5 (2001), *available at* http://mydocs.epri.com/docs/public/000000000001006892.pdf.

110. E.D. TATE & PETER SAVAGIAN, THE CO2 BENEFITS OF ELECTRIFICATION: E-REVS, PHEVS, AND CHARGING SCENERIOS 10 (General Motors Corp. 2009).

111. K. PARKS, P. DENHOLM & T. MARKEL, COSTS AND EMISSIONS ASSOCIATED WITH PLUG-IN HYBRID ELECTRIC VEHICLE CHARGING IN THE XCEL ENERGY COLORADO SERVICE TERRITORY 12 Tbl 3 (Nat'l Renewable Energy Lab. 2007), *available at* http://www.nrel.gov/docs/fy07osti/41410.pdf.

112. *Id.*

113. MICHAEL KINTNER-MEYER, KEVIN SCHNEIDER, & ROBERT PRATT, *IMPACTS ASSESSMENT OF PLUG-IN HYBRID VEHICLES ON ELECTRIC UTILITIES AND REGIONAL U.S. POWER GRIDS* 1-6 (Pac.Nw. Nat'l Lab. 2007), *available at* www.ferc.gov/about/com-mem/wellinghoff/5-24-07-technical-analy-wellinghoff.pdf.

is more efficient than gasoline; and using electricity will facilitate reduction of greenhouse gas emissions. When it comes to powering the LDV fleet, electricity is superior to all other alternative fuels.

1. Using Electricity Promotes Fuel Diversity

America's vehicles currently are powered almost exclusively by fuel derived from crude oil.[114] Electricity, in contrast, is generated by a diverse set of fuels.[115] An electrically-powered transportation system, therefore, is one in which an interruption of the supply of one fuel can be made up for by others, even in the short-term, at least to the extent that there is spare capacity in generators fueled by other fuels, which is generally the case.[116] Similarly, price volatility for one fuel is dampened by price stability in others. Lastly, the ability to use different fuels as a source of power increases the flexibility of an electrified light duty vehicle fleet. As our national goals and resources change over time, we can shift transportation fuels without overhauling our transportation infrastructure. In short, an electrified transport system would offer much greater control over the fuels we use to support the transportation sector of our economy.

2. Domestic Fuels Generate Electricity

While oil supplies are subject to a wide range of geopolitical risks, the fuels that we use to generate electricity are generally sourced domestically. All renewable energy is generated using domestic resources. We are a net exporter of coal,[117] from which we generate about half our electricity.[118] Although we currently import approximately sixteen percent of the natural gas we consume,[119] over ninety percent of those imports were from North America in 2008.[120] More importantly, perhaps, is that we do not rely, yet, on a global natural gas market, which could expose us to the same types of vulnerabilities with respect to our natural gas supplies that we currently face with our oil supplies.[121]

Though we import a substantial portion of the uranium we use for civilian nuclear power reactors, forty-two percent of those imports, are from Canada and Australia.[122] Moreover, although we rely more on imported uranium than other fuels in the electric power sector, over half of uranium purchases are pursuant to medium-term or long-term contracts that contain fixed price or base-escalated pricing provisions,[123] which limit the effects of uranium price volatility. Further, the cost of fuel represents a much smaller portion of overall costs at nuclear plants than at other non-renewable energy power generating stations.[124] Therefore, even when uranium prices are volatile, that volatility is not reflected in the price of power generated at nuclear plants.

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114. *Annual Energy Review 2008*, *supra* note 18, at v.

115. DOE, EIA, *Electric Power Annual 2007*, at 2 (2009) *available at* www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html. [hereinafter, *Electric Annual 2007*]

116. *Id.* at 102.

117. Fred Freme, DOE EIA, *U.S. Coal Supply and Demand 2008 Review*, at 11-13 (2009) *available at* www.eia.doe.gov/cneaf/coal/page/special/article_dc.pdf.

118. *Electric Annual 2007*, *supra* note 217, at 2.

119. *Annual Energy Outlook 2009*, *supra* note 32, at 78.

120. *Annual Energy Review 2008*, *supra* note 18, at 191.

121. *See, e.g.*, Monika Ehrman, *Competition Is A Sin: An Evaluation of the Formation and Effects of a Natural Gas OPEC,* 27 ENERGY L. J. 175 (2006).

122. DOE, EIA, *2008 Uranium Marketing Annual Report,* at 1 (2009), *available at* http://www.eia.doe.gov/cneaf/nuclear/umar/umar.html [hereinafter, *Uranium Report*].

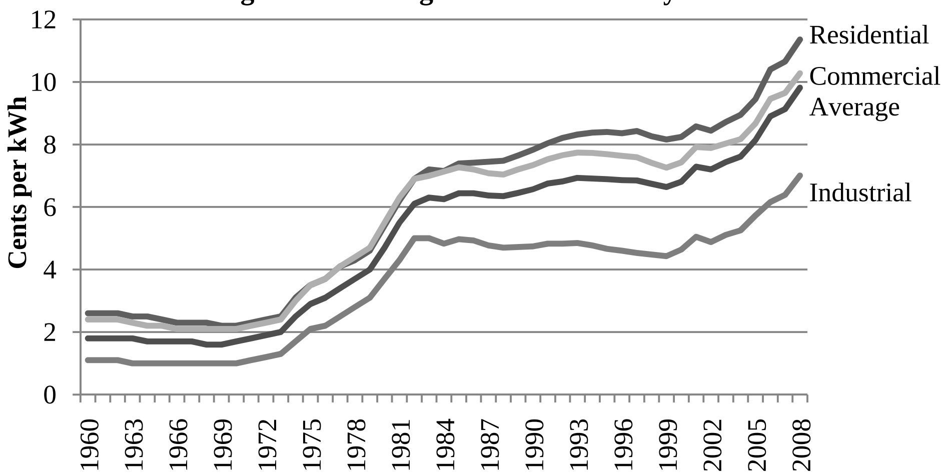
123. *Id.*

124. Nuclear Energy Inst., *Costs: Fuel, Operation and Waste Disposal,* www.nei.org/resourcesandstats/nuclear_statistics/costs/ (last visited Sept. 11, 2009).

3. Electricity Prices Are Less Volatile Than Oil and Gasoline Prices

Electricity prices are significantly less volatile than oil or gasoline prices. As depicted in Figure 11, over the past twenty-five years, electricity prices have risen steadily but slowly. Since 1983, the average retail price of electricity delivered in the United States has risen by an average of less than two percent per year.[125] Moreover, prices have risen by more than five percent per year only three times in that same time period.[126] This price stability exists for at least two reasons.

Figure 10: Average Price of Electricity 1960-2008



First, the retail price of electricity reflects a wide range of costs, only a small portion of which is the underlying cost of the fuel. The remaining costs are largely fixed.[127] In most instances, the cost of power plant fuel represents a smaller percentage of the overall cost of delivered electricity than the cost of crude oil represents as a percentage of the overall cost of retail gasoline.[128] This cost structure promotes price stability with respect to the final retail price of electricity.

Second, although real-time electricity prices are volatile, sometimes highly volatile on an hour-to-hour or day-to-day basis,[129] power prices are relatively stable over the medium-term and long-term. Therefore, in setting retail rates, utilities or power marketers use formulas that will allow them to recover their costs, including the occasionally high real-time prices for electricity, but which effectively isolate the retail consumer from the hour-to-hour and day-to-day volatility of the real-time power markets.[130] By isolating the consumer from the price volatility of the underlying fuel costs, electric utilities would be providing to drivers of GEVs the very stability that oil companies cannot provide to consumers of gasoline.

125. *Annual Energy Review 2008*, *supra* note 18, at 261.

126. *Id.*

127. DOE, EIA, *Energy in Brief-What Everyone Should Know: How is my Electricity Generated, Delivered, and Priced?*, tonto.eia.doe.gov/energy_in_brief/electricity.cfm (last visited, Sept. 11, 2009) [hereinafter, *Energy Brief*].

128. *See* DOE, EIA, *A Primer on Gasoline Prices*, (2008), *available at* www.eia.doe.gov/bookshelf/brochures/gasolinepricesprimer/; *Electric Annual 2007*, *supra* note 217, at 69.

129. SUSTAINABLE ENERGY ADVANTAGE, L.L.C., USING WIND POWER TO HEDGE VOLATILE ELECTRICITY PRICES FOR COMMERCIAL AND INDUSTRIAL CUSTOMERS IN NEW YORK at 2-3 (2003), *available at* www.powernaturally.org/About/documents/WindHedgeExSumm.pdf.

130. *Energy Brief*, *supra* note 229.

4. Use of Grid-Enabled Vehicles Reduces Carbon Emissions and Energy Consumption

Using GEVs reduces carbon emissions as compared to petroleum-fueled vehicles. While emission reductions are greater if the GEV is recharged using electricity generated from a renewable resource, several well-to-wheels analyses conclude that even vehicles powered by the current mix of fuel sources in the United States will produce substantially lower carbon emissions than conventional vehicles.

Well-to-wheels analyses examine emissions attributable to the use of a fuel from the time an energy source is extracted until it is consumed by a vehicle.[131] In 2007, the Natural Resources Defense Council (NDRC) and the Electric Power Research Institute (EPRI) published a well-to-wheels analysis of several different automotive technologies fueled by a range of fuels commonly used to generate power.[132] Its analysis concluded that using a PHEV would reduce carbon emissions as compared to a petroleum-fueled vehicle, even if all of the exogenous electricity used to recharge the PHEV was generated at an old (relatively dirty) coal power plant. Whereas a conventional gasoline vehicle would be responsible for emissions, on average, of 450 grams of CO_2 per mile, a PHEV that was recharged with power generated at an old coal plant would be responsible for emissions of about 325 grams of CO_2 per mile, a reduction of about twenty-five percent.[133] Emissions attributable to the vehicle could be reduced to as low as 150 grams of CO_2 per mile if the exogenous power was generated at a plant without carbon emissions and ranged between 200 and 300 grams of CO_2 per mile if the power used were generated using any other fossil fuels and generation technologies.[134] Therefore, the NRDC study demonstrated that no matter how the exogenous power consumed by a PHEV was generated, the overall level of emissions attributable to its operation would be lower compared to a conventional vehicle.[135]

The results of the NRDC/EPRI study were consistent with an MIT study that examined the same issue.[136] That study included an integrated well-to-wheels analysis of the different vehicle technologies to determine their relative level of carbon emissions and energy usage. The study concluded that PHEV-10s, PHEV-30s, PHEV-60s, and EVs use less energy on a well-to-wheels basis than petroleum-fueled conventional vehicles.[137] While a conventional vehicle consumes 3.35 MJ/km of energy, the various types of PHEVs and the EV consume 1.16, 1.24, 1.32, and 1.79 MJ/km respectively.[138] Their increased efficiency is reflected in their reduced level of carbon emissions, with the PHEVs and EVs emitting 84.3, 86.2, 89.8, and 115.6 grams of CO_2/km as compared to a conventional vehicle's emission of 251.7 grams of CO_2/km.[139] These two studies are consistent with the results of numerous other analyses that have examined this issue and found that the emissions profile of PHEVs and EVs is always superior to an ICE-powered vehicle.[140] Accordingly, even if one powers a PHEV or EV with electricity generated

131. MATTHEW A. KROMER & JOHN B. HEYWOOD, ELECTRIC POWERTRAINS: OPPORTUNITIES AND CHALLENGES IN THE U.S. LIGHT-DUTY VEHICLE FLEET at 24 (MIT 2007), *available at* web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf.

132. NRDC & CHARLES CLARK GROUP, ENVIRONMENTAL ASSESSMENT OF PLUG-IN HYBRID ELECTRIC VEHICLES: VOLUME 1: NATIONWIDE GREENHOUSE GAS EMISSIONS (EPRI 2007), *available at* mydocs.epri.com/docs/public/000000000001015325.pdf.

133. *Id*. at 7.

134. *Id.*

135. *Id*.

136. Kromer & Heywood, *supra* note 237.

137. *Id.* at 115

138. *Id.*

139. *Id.*

140. *See, e.g.*, Constantine Samaras & Kyle Meisterling, *Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy*, 42 ENV'T. SCI. TECH. 3170–3176 (2008); Tate & Savagian, *supra* note 210; Christopher Yang & Ryan McCarthy, *Electricity Grid Impacts of Plug-In Electric Vehicle Charging, available at* pubs.its.ucdavis.edu/download_pdf.php?id=1290 (last visited Sept. 11, 2009).

at an old coal plant, overall carbon emissions will be lower than emissions from a traditional internal combustion engine. And to the extent that the electricity used to power the vehicle is generated at a power plant with fewer carbon emissions than an old coal plant, the carbon emissions profile of the PHEV or EV will improve as well.

5. Using Electricity Will Further Facilitate Reduction of Greenhouse Gas Emissions

The light-duty fleet is responsible for about 17.5 percent of U.S. greenhouse gas emissions.[141] Running cars on electricity offers advantages in dealing with greenhouse gas emissions both at the demand (vehicle) level and at the supply (generation) level. In the absence of greenhouse gas emission regulation, the extent to which the use of GEVs reduces greenhouse gas emissions will be a function of the marginal generation fuel used by the utility generating the electricity. But as just explained in Section IV.C.4 above, no matter what fuel is used to generate the power consumed by GEVs, the vehicle is responsible for lower carbon emissions even if the power it uses is generated from coal.

But perhaps of greater importance is that once GEVs are in place, their emissions profile will continue to improve without any additional changes to the vehicle, as the emissions profile of our power generating plants improve. At the moment, there are over 250 million LDVs on the road, each burning fuel and emitting carbon dioxide.[142] To achieve improvements in their cumulative emissions profile, improvements must be made in the emissions profile of each vehicle, one at a time. An electric-powered vehicle fleet, however, would circumscribe the challenge of reducing those carbon emissions to roughly 6,900 coal and natural gas generation plants that comprise over eighty percent of the nation's power generating capacity.[143] It is far simpler to sequester carbon or employ renewable energy at the power plant than the tailpipe. Indeed, analyses of the cost of greenhouse gas emission reductions routinely find that it is more expensive to reduce emissions from vehicles than from power plants. Therefore, proportionately more emission reductions will come from power plants that from vehicles.[144] By shifting the emissions stream created by vehicles from their tailpipes to central power stations, we will both facilitate and lower the costs of combating climate change.

V. EVALUATING THE COMPETITION

The perils of relying on fuel derived from crude oil are well known. Yet, there are only a limited number of possible alternatives to gasoline or diesel, including alternative liquid fuels, hydrogen, natural gas, and electricity. In addition to the reasons stated above, the nation should pursue a path of electrification because every other alternative fails to meet several critical objectives. The shortcomings of biofuels are addressed above. Neither of the two other potential alternatives, natural gas and hydrogen, is a compelling alternative to electrification.

A. Natural Gas

A growing chorus of analysts and observers point to natural gas as a potential game-changer in transportation because of its ability to satisfy multiple constraints, such as

141. Raymond J. Kopp, *Issue Brief 12: Transport Policies to Reduce CO2 Emissions from the Light-Duty Vehicle Fleet*, at 163 *available at* www.rff.org/rff/Publications/upload/31815_1.pdf.

142. RESEARCH & INNOVATIVE TECH. ADMIN., BUREAU OF TRANSP. STATISTICS, TBL 1-11: NUMBER OF U.S. AIRCRAFT, VEHICLES, VESSELS, AND OTHER CONVEYANCES (U.S. Dep't of Transp. 2009), *available at* www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html.

143. *Electric Power Annual 2007*, *supra* note 217, at 25.

144. *See, e.g.*, DOE, EIA, *Energy Market Impacts of Alternative Greenhouse Gas Intensity Reduction Goals*, at 18 (2006), *available at* www.eia.doe.gov/oiaf/servicerpt/agg/pdf/sroiaf(2006)01.pdf.

sustainability, affordability, and security.[145] While natural gas has a critical role to play in the United States' energy future, is should not be as an alternative to petroleum in short-haul transport vehicles. Instead, for several reasons, natural gas makes the most sense in the electric power sector and, perhaps, in fleet vehicles with central refueling stations.

First, consuming natural gas emits about thirty percent less CO_2 than oil and forty percent less CO_2 than coal on an energy equivalent basis,[146] a calculation that does not take into account the platform in which the fuel is consumed. On average, internal combustion engines currently achieve an efficiency rating of just twenty to thirty percent.[147] Meanwhile, the fleet of U.S. coal power plants currently rates at thirty percent.[148] The current gas fleet reaches roughly forty-three percent, and has been improving substantially as combined cycle gas plants are deployed in greater numbers.[149] Current generation combined cycle plants reach efficiency levels of sixty percent,[150] which, when combined with the lower carbon profile of gas, results in an emissions reduction of about seventy percent per unit of electricity generated versus the coal fleet.[151]

Second, natural gas is currently a largely domestic fuel. In 2008, dry domestic natural gas production equated to eighty-nine percent of total natural gas consumed in the United States.[152] In addition, ninety percent of U.S. gross natural gas imports came from Canada.[153] Only a small fraction—about 1.5 percent—of U.S. gas supplies came from the global liquefied natural gas (LNG) market in 2008.[154] This was just below the all-time high in 2007 of about three percent.[155] It is important to note, however, that domestic natural gas prices have historically tracked international oil prices, which raises concerns about price volatility. During the summer of 2008, U.S. natural gas futures prices spiked as high as $13.58 per million Btu on the New York Mercantile Exchange (NYMEX).[156] Figure 11 plots NYMEX oil prices versus natural gas prices on a Btu equivalent basis since 1994.[157]

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145. *See, e.g.*, T. Boone Pickens & Ted Turner, *New Priorities For Our Energy Future*, WALL ST. J., Aug. 17, 2009, *available at* http://online.wsj.com/article/SB20001424052970203863204574348432504983734.html.

146. DOE, EIA, *Natural Gas Issues and Trends*, at 58 (1999), *available at* http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/natural_gas_1998_issues_trends/pdf/chapter2.pdf.

147. DOE, EERE, *Advanced Combustion and Emissions Control Technical Roadmap for Light-Duty Powertrains*, at 8 (2006), *available at* http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/acec_roadmap.pdf.

148. János M.Beér, *Higher Efficiency Power Generation Reduces Emissions: National Coal Council Issue Paper*, at 2 (2009), *available at* http://web.mit.edu/mitei/docs/reports/beer-emissions.pdf.

149. *Annual Energy Outlook 2009*, *supra* note 32, at 126, 135 (2009) (assumes natural gas heat content of 1,028 Btu per cubic foot and 3,412 Btu per kilo-watt hour).

150. GE Energy, *Gas Turbine and Combined Cycle Products*, at 4, *available at* www.gepower.com/prod_serv/products/gas_turbines_cc/en/downloads/gasturbine_cc_products.pdf.

151. Authors' calculations assuming natural gas contains 45% less carbon than coal and comparing a combined cycle gas turbine (60% efficiency) to the existing coal fleet (32% efficiency).

152. *Annual Energy Review 2008*, *supra* note 18, at 187.

153. *Id.* at 191.

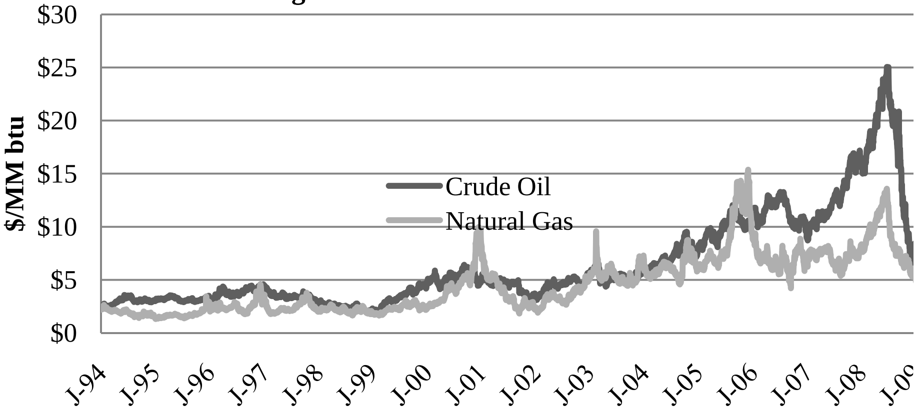
154. DOE, EIA, *Natural Gas Monthly, July 2009*, Tbls 1 & 4 (2009) (for author's calculations).

155. *Annual Energy Outlook 2009*, *supra* note 32, at 135.

156. DOE, EIA, *Natural Gas Navigator: Daily Natural Gas Futures: Contract 1*, tonto.eia.doe.gov/dnav/ng/hist/rngc1d.htm (last visited, Sept. 11, 2009) [hereinafter, *Natural Gas Navigator*].

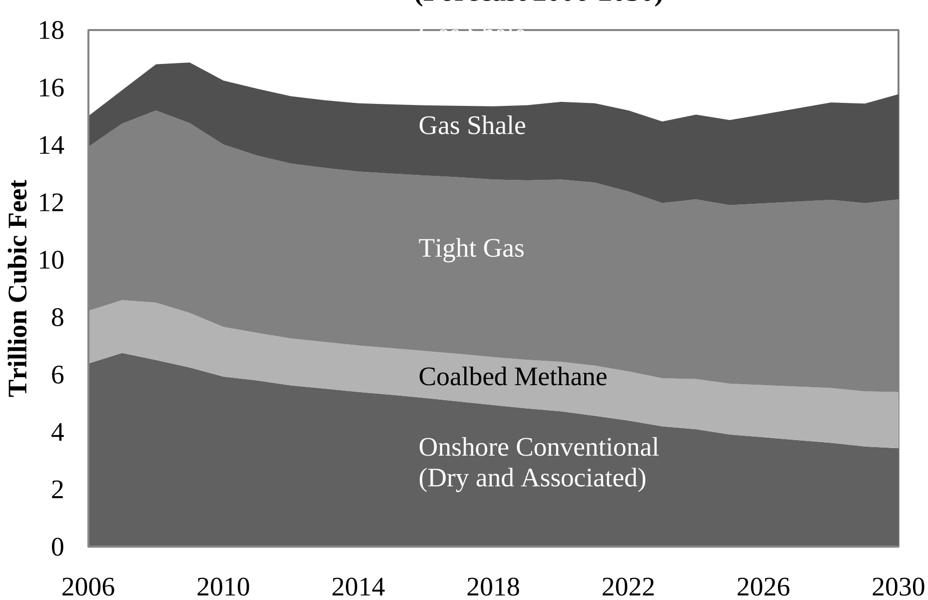
157. *Id.*; DOE, EIA, *Petroleum Navigator: NYMEX Futures Prices*, *available at* tonto.eia.doe.gov/dnav/pet/pet_pri_fut_s1_d.htm (last visited Sept. 11, 2009).

Figure 11: NYMEX Contract 1



Finally, mounting evidence suggests that the United States may have an abundance of domestic natural gas. Just a few years ago, most analysts had concluded that U.S. gas production was in an irrevocable free-fall.[158] By early 2008, however, U.S. gas markets were being completely reshaped by advances in the recovery of gas resources from unconventional reservoirs like shale gas, coal bed methane, and tight gas. The estimates vary widely, but consensus seems to be settling on undiscovered technical recoverable reserves well in excess of 1,000 tcf. In June of 2009, the Potential Gas Committee at the University of Colorado estimated that total U.S. reserves—proved, probable, possible, and speculative—were in excess of 2,000 trillion cubic feet.[159] By way of comparison, BP reports that current U.S. proved gas reserves are just over 200 tcf.[160] One look at Figure 12 tells the story.

Figure 12: Lower-48 Onshore Dry Natural Gas Production (Forecast 2006-2030)



158. *See e.g.*, ROBERT L. HIRSCH, *PEAKING OF WORLD OIL PRODUCTION: IMPACTS, MITIGATION, AND RISK MANAGEMENT* 33-36 (National Energy Tech. Lab. 2005).

159. Potential Gas Comm., *Potential Supply of Natural Gas in the United States*, at Slide 4, Dec. 31, 2008, *available at*, http://www.aga.org/NR/rdonlyres/D4CFEBEB-81B3-4219-9800-6FFDDC7FCD1D/0/0906PGC.pdf.

160. BP, Statistical Review of World Energy 2009, *supra* note 2, at 22.

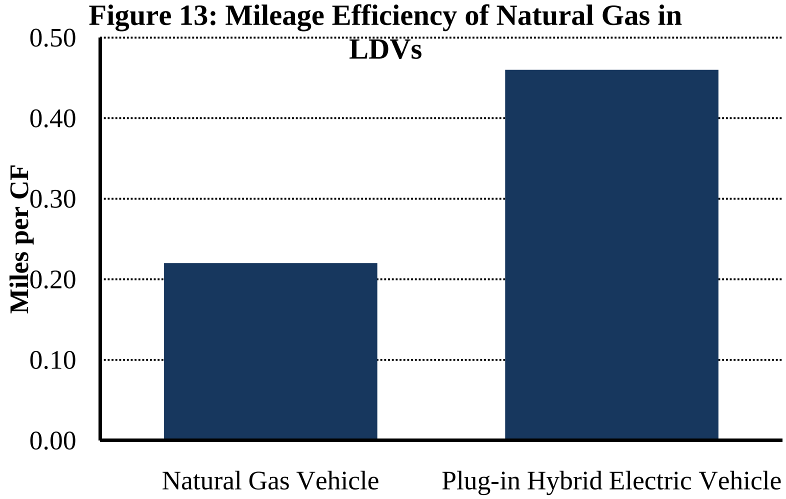
With conventional production in rapid decline, shales, coal bed methane, and tight gas are expected to keep lower forty-eight onshore production steady for the next two decades. Yet, at least two significant questions exist regarding the future of unconventional gas remain.

To extract unconventional natural gas, producers must over-pressurize the source rock, creating multiple fractures in which gas supplies can accumulate. The fracturing process is typically achieved using fluids like water under high pressure along with viscosity-enhancing chemical agents. In addition, producers typically inject a proppant, or propping agent, into the well in order to keep the fractures from closing when pressure is reduced.[161]

As unconventional gas production grows more common, some externalities of hydraulic fracturing may be coming into focus. Concerns about the impact on water wells spurred debate in Congress in 2009, and there is a growing call for EPA to start regulating hydraulic fracturing to protect drinking water. Further, the broader issue of freshwater access is likely to emerge as a challenge for the industry, particularly in the Western United States. A typical shale well using hydraulic fracturing consumes 3.4 million gallons of fresh water.[162] Water treatment options certainly exist, but recycling is not currently the norm.[163]

The second question mark for unconventional gas is the cost of production—or perhaps more importantly, the price of natural gas required to support ongoing capital expenses in unconventional production. Natural gas production wells have steep decline rates. According to published company reports, the first year decline rate for a typical well in the Haynesville shale play is eighty-one percent; the second year rate is thirty-four percent and the third year rate is twenty-two percent.[164] Bernstein Research report recently estimated that Haynesville operators needed a natural gas price of nearly $8 per million Btu to earn a nine percent return on average capital employed.[165] Throughout 2009, natural gas prices have been far below this, and the pressure on shale operators to postpone new drilling has been immense.

Figure 13: Mileage Efficiency of Natural Gas in LDVs



Setting aside these challenges, the real dilemma seems to be how best to use natural gas. It seems illogical to take natural gas out of combined cycle gas plants and burn it in internal combustion engines. A comparative energy efficiency analysis of the "tank to wheels" conversion of a

161. EPA, Underground Injection Control Program, *Hydraulic Fracturing*, *available at* www.epa.gov/ogwdw000/uic/wells_hydrofrac.html.

162. *See* Chesapeake Energy, *Natural Gas Production*, *available at* www.askchesapeake.com/Barnett/Multimedia/Brochures/Water%20Use%20in%20Barnett%20Deep%20Shale%20Gas%20Exploration%20May%202009_Rev%201.pdf (for Chesapeake Energy's discussion of water recycling).

163. *See* Chesapeake Energy, Natural Gas Production, *available at* www.askchesapeake.com/Barnett/Production/Pages/WaterManagement.aspx, (last visited Aug. 25, 2009) (for a second Chesapeake Energy discussion on water recycling).

164. Goodrich Petroleum Corp., Haynesville Shale Overview, Presentation at EnerCom Oil & Services Conference VII (Feb. 18-19, 2009) at 19, *available at* www.doodrichpetroleum.com/presentations/20090213_EnerCom.pdf.

165. Bernstein Research, *Why the Haynesville (and Other Plays) Won't Work at $4, $5, or $6/mcf Gas*, BERNSTEIN COMMODITIES AND POWER, Mar. 27, 2009.

given amount of natural gas to vehicle miles with competing technologies—such as PHEVs—demonstrates this shortcoming. A current generation CNG vehicle gets approximately 28 miles per gallon of gas equivalent (GGE)—the mileage of the Honda Civic GX. There are 127 cubic feet (CF) of natural gas per GGE.[166] One thousand cubic feet (mcf) of natural gas will, therefore, provide about 220 miles of vehicle range when burned in a CNG internal combustion engine.[167] Comparatively, the same one thousand cubic feet of natural gas will provide 457 miles of vehicle range, or 0.46 miles per cubic foot of natural gas, when it is burned in a state-of-the-art combined cycle natural gas plant that provides electricity to a plug-in hybrid electric vehicle.[168] In other words, a PHEV powered by electricity generated in an efficient natural gas generator is about twice as fuel efficient as the NGV. While this is a simplification, this basic efficiency question is one that should be key to determining whether NGVs or electric vehicles are more likely to form the basis of a post-petroleum transportation sector.

There are also substantial drawbacks in distribution of natural gas for NGVs and in the demand side—vehicles—as well. Use of natural gas for surface transportation would require the development of significant new infrastructure that is difficult to justify. While both NGVs and GEVs will require new infrastructure for refueling or recharging, they face different barriers when it comes to refueling. The electric grid already reaches nearly every building in the United States. Although some grid upgrades and the provision of public charging infrastructure would be necessary, the underlying infrastructure is already in place, and a substantial portion of grid improvements will be made in any event as part of the evolution of the smart grid. In contrast, creating a refueling infrastructure for natural gas powered cars would be a significant undertaking, especially in those regions of the United States that do not already have networks for delivery of natural gas to residences and businesses.

Furthermore, refueling stations might be needed more than gas stations for a similar number of vehicles (NGVs tend to have a shorter range than gasoline or diesel fueled vehicles because at ambient temperature, methane is not a dense fuel).[169] Vehicle range, therefore, will always be a challenge for natural gas, which is much better suited to combustion in stationary power plants.

Finally, using natural gas means investing significant resources while remaining reliant on a single fuel. Setting aside all other propositions, this simple fact disadvantages NGVs to electrification. Investing in a technology that allows for the diversification of fuels instead of the concentration of risk in another fuel is a better way to enhance our energy and economic security.

B. Hydrogen

In the early part of this decade, there was a sense that hydrogen-fueled vehicles would provide the answer to our energy security problems. There was significant public discussion and excitement about the development of a hydrogen economy. Yet, over time, much of that excitement abated as attention turned first to biofuels and then to electricity.

Because hydrogen-powered vehicles use electric drive-trains, they share many components with GEVs. In fact, as fuel cell technology progresses and the cost of fuel cells fall, hydrogen vehicles may be a successor or supplement to battery-powered electric vehicles. Yet, at the present time, however, electrification is a more viable and cost-effective proposition.

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166 Christine & Scott Gable, *Fuel Energy Comparisons: Gasoline Gallon Equivalents (GGE),* for About.com

167 1,000 cubic feet of natural gas equals 7.87 GGE. If the Civic gets 28 miles per GGE, the vehicle range is about 220 miles.

168 Assumes a natural gas plant heat rate of 7000 Btu per kWh, which generates about 142 kWh of electricity, 20 percent line loss and PHEV efficiency of four miles per kWh. (1,000,000 BTU/7,000 BTU per kWh)*0.80*4 miles per kWh).

169. *Annual Energy Outlook 2009*, *supra* note 3, at 43.

Commercialization of hydrogen-fueled vehicles faces several challenges that are greater obstacles than those facing battery-powered, grid-connected vehicles. First, there is no clear ability to manufacture sufficient quantities of hydrogen to fuel the automotive fleet. The United States currently manufactures about 9 million metric tons of hydrogen per year for industrial use.[170] That volume is the energy equivalent of about 190 million barrels of oil, less than a ten day supply for the nation.[171] To replace just the portion of oil that is used for short-haul transportation, the nation would have to increase its production of hydrogen by over thirty times. Moreover, most of the hydrogen produced in the United States is produced from natural gas,[172, 173] and we believe that rather than diverting a substantial portion of the nation's natural gas to produce hydrogen for vehicles, the gas resources should dedicated to power generation, which is a more efficient use of the fuel. While hydrogen can be produced by electrolyzing water, that process is particularly expensive, and the faster you make the hydrogen, the more energy the process consumes.[174] In fact, to produce enough hydrogen to replace the gasoline we consume today would take more electricity than is currently generated in the entire nation.[175]

Second, reliance on hydrogen would require the construction of an entirely new infrastructure to distribute it to consumers. Third, the use of hydrogen raises several safety issues. Hydrogen is highly flammable and easily ignitable.[176] Also, because hydrogen molecules are so small, they leak easily.[177] Moreover, the gas is clear and burns invisibly, making it difficult to tell if it has leaked or is on fire.[178] Fourth, hydrogen fuel cells are significantly more expensive than petroleum or GEVs. While batteries currently make GEVs more expensive than conventional gasoline-powered ones, fuel cells are more expensive, though how much so is unclear because having never been produced at scale it is difficult to estimate manufacturing costs. Nevertheless, most experts agree that hydrogen fuel cells seem to be much further away from commercialization than batteries.[179]

Finally, perhaps the largest obstacle to the development of a hydrogen-fueled light-duty fleet is the fact that hydrogen itself is much more expensive than electricity, and likely always will be. Hydrogen is not a source of new energy, but a carrier of energy processed from either natural gas or with the use of electricity. The process of producing hydrogen, preparing it for transport, distributing it, and converting it back into electricity is itself energy intensive and can consume as much as seventy-five percent of the initially available energy.[180] In contrast, transmission losses from the distribution of electricity, the same electricity that can be used to either make hydrogen or power cars directly, have averaged just below ten percent in recent years.[181] While it is difficult to predict the nature of future technological developments, it may prove to be very difficult for hydrogen to overcome this price disparity.

170. DOE, EERE, *U.S. Dep't of Energy Hydrogen Program*, at 2 (2009), *available at* www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_program.pdf.

171. JOSEPH J. ROMM, THE HYPE ABOUT HYDROGEN 72 (Island Press 2004) (calculation by authors based on conversion ratio).

172. DOE, *National Hydrogen Energy Roadmap*, at 7 (2002), *available at* www1.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf.

173. Worldwide, approximately 48% of hydrogen is produced from natural gas, 30% from oil, 18% from coal and the remainder from electrolysis. Romm, *supra* note 309, at 72.

174. *Id*., at 75.

175. *Id*. at 76.

176. *Id*. at 105.

177. *Id*. at 105.

178. *Id*. at 106.

179. *Id.;* Stephen Power, *Energy Secretary, Congress Collide Over Hydrogen Car Funds*, WALL ST. J., July 28, 2009, at A6; Ulf Bossel, Presentation at "Intelec '05" at Berlin, On the Way to a Sustainable Energy Future, at 6 (Sept. 18 -22, 2005), *available at* www.efcf.com/reports/E15.pdf.

180. *Id.*

181. *Annual Energy Review 2008*, *supra* note 18, at 66.

VI. THE PATH FORWARD

Given the immense costs that oil dependence imposes on our economy, and the shortcomings of biofuels, natural gas and hydrogen as workable alternatives to petroleum as a fuel for the light-duty fleet, electrification is the best opportunity to address the nation's oil dependence. Because of the diverse interests of many participants in the electric and automotive industries, however, it will be difficult for all of the relevant parties to come together to develop an efficient strategy for the wide scale deployment of GEVs. Given the great importance of this issue to the nation, we believe that the government must help facilitate this process.

A. Deployment Challenges

While deployment of GEVs will be a complex process with a myriad of challenges, there are four main challenges that must be addressed to facilitate GEV deployment:

- Battery performance must improve and costs must be reduced;
- Charging infrastructure must be deployed;
- Utilities must upgrade systems to accommodate GEVs; and,
- Consumers must accept vehicles whose ownership and operation is different than existing vehicles.

First, battery technology must be improved to reduce the cost, improve the energy density, and extend the life of existing batteries. Congress and President Obama took significant steps forward in this regard with the American Recovery and Reinvestment Act of 2009.[182] Yet this one time expenditure is enough. Reducing the cost of batteries to consumers is the most critical step to make the total cost of ownership of a GEV competitive with a traditional internal combustion engine powered vehicle. It will be necessary to dedicate more funds to this effort.

Second, recharging infrastructure must be deployed. While home charging will be important for achieving high rates of GEV deployment, public charging is arguably more important for moving past the very early stages of GEV adoption. Drivers are accustomed to being able to fill up using the ubiquitous gasoline infrastructure developed over the last 100 years. Inability to do so will generate significant hesitancy— range anxiety—for many drivers, and may reduce overall efficiency of PHEVs. Especially early on, a readily available network of Level II public charging facilities may assist in minimizing range anxiety. It should be supplemented by public Level III chargers capable of providing a high voltage "fast charge" that can charge vehicle batteries in minutes rather than hours. Level III facilities will allow a fast charge for a driver who forgot to or was unable to charge overnight, or who is travelling beyond the range of the vehicle without the time to stop and wait for a slower charge.

GEV advocates have suggested that private firms should install public charging infrastructure. However, a profitable business model for public charging infrastructure has not been demonstrated. The only way for consumers to recover the cost of an expensive battery is to defray it over time with comparatively cheap electricity. This upper bound on the price consumers are willing to pay to charge their vehicles, and the availability of home charging, limits what consumers will be willing to pay for public charging. Moreover, at the moment, the payback period on public chargers seems to far exceed the life of the equipment. Unless this challenge is addressed, it is difficult to see how public charging infrastructure will be deployed at scale.

182. American Recovery and Reinvestment Act, Pub. L. No. 111-5, 123 Stat. 115 (2009).

Third, GEVs represent an enormous opportunity for the nation's electric utilities and electricity market retailers in both regulated and competitive electricity markets. Light-duty vehicles today are the largest energy consumers in the transportation sector, which is the most significant sector of the economy that relies on some form of energy other than electricity. The nation currently consumes about 4.1 trillion kWh of electric power each year. If 150 million light-duty GEVs each consume 8 kWh of power a day, that would represent an additional 440 billion kWh of power consumed each year.

Depending on the manner in which that power is consumed, there will be relatively little need for additional generating capacity at first; much of the vehicle charging can take place during off-peak hours when significant generating capacity is typically idle. Moreover, by flattening the load curve and increasing the utilization rates of existing power generating plants, utilities should be able to spread their fixed costs over a greater volume of power and reduce maintenance costs, perhaps lowering costs for all of their customers.

While adding millions of GEVs as customers is a great opportunity for utilities, it will require them to address several issues. Some utilities will have to upgrade distribution level transformers to ensure reliable service to homes and other charging locations. Along with investments in smart meters and smart charging software, utilities will need to invest in IT infrastructure to support a range of smart grid applications including GEVs. Further, both utilities and electricity market retailers will need new rate plans to reliably serve GEVs.

Fourth, new innovations often require many years to become widely adopted in the marketplace. Making a successful entrance into a competitive automobile market established a century ago is no easy task. Traditional gasoline-electric hybrid vehicles have so far failed to overcome the hurdles, accounting for approximately 3 percent of new vehicle sales in 2008. To a degree, hybrids have demonstrated their potential among early adopters and with automobile manufacturers. However, without a change in consumer attitude, widespread consumer acceptance of electrification remains a difficult proposition. The market for these technologies will only reach a "take-off" point if they can offer a compelling alternative to conventional IC engines on either cost or performance grounds.

B. Deployment Policies

1. Electrification Deployment Clusters (Ecosystems)

To achieve wide-scale deployment of grid-enabled vehicles, the government should undertake a program to establish electrification ecosystems in a number of American cities. In the GEV context, an electrification ecosystem is a community in which each of the elements necessary for the successful deployment of grid-enabled vehicles is deployed nearly simultaneously in high concentrations. By ensuring that vehicles, infrastructure, and the full network of support services and technologies arrive in well-defined markets together, ecosystems will provide an invaluable demonstration of the benefits of integrated electrification architecture. Electrification ecosystems will:

- Demonstrate Proof of Concept: By demonstrating the benefits of grid-enabled vehicles in a real world environment, ecosystems will make consumers aware of the tremendous potential of electrification.
- Drive Economies of Scale: Electrification ecosystems will allow market participants to take advantage of economies of scale, particularly with regard to charging infrastructure. They will also drive demand for grid-enabled vehicles at a rate that is likely to be far in excess of the rate if the vehicles are simply purchased by early adopters scattered around the United States.

- Facilitate Learning by Doing: Electrification ecosystems will play a feedback role in the GEV innovation process. Data aggregation and concentration of efforts will be informative to new innovation.

Ecosystem cities should be chosen by the Department of Energy on a competitive basis similar to the Department of Education's recent "Race to the Top" program. Successful bids would ideally be submitted by a coalition of entities in a community reflecting wide support for GEV deployment. Such coalitions should reflect the support of: state and local government, the applicable Public Utility Commission, local utilities, large local employers, and others.

A phased process will maximize the effectiveness of the electrification ecosystem concept. Phase one ecosystems should each reach stock penetration rates of 50,000 to 100,000 vehicles within four to five years. Massing that many vehicles in a limited number of communities will prove that GEVs can work at scale and allow researchers to generate a large enough data set to evaluate GEV usage patterns.

Phase one of the ecosystem deployment strategy is intended primarily as a proof of concept and data collection exercise. The goal is primarily to take advantage of economies of scale in a handful of cities to deploy relatively large numbers of GEVs in order to build consumer confidence and accelerate the learning process. The lessons learned in those communities will help other cities determine how much charging infrastructure is necessary and where it should go, when drivers will charge their vehicles, how much they are willing to pay to charge their vehicles, to what extent their charging patterns will be affected by the price of electricity, and what business models might be most successful.

Phase two of the deployment strategy would expand deployment to between 20 and 25 additional cities. At the same time, as the GEV concept is proved, battery costs decline, and infrastructure deployment becomes more efficient, government support for ecosystems also should decline.

The government should offer a package of benefits to communities that are selected as ecosystems. Purchasers of GEVs registered in ecosystems should be eligible for tax credits sufficient to cover nearly the entire incremental cost of the vehicles over similarly equipped internal combustion engine vehicles. This will help direct sales of GEVs to the ecosystems. Utilities should be eligible for tax credits to upgrade their systems to support GEVs and entities deploying public charging infrastructure should be eligible for large subsidies.

2. Other Policies

Developing ecosystems alone will be insufficient to facilitate GEV deployment. Other policies will be required, including, but not limited to programs to help bring battery costs down and to transform the necessary manufacturing infrastructure. To help drive scale and promote the manufacture of automotive grade lithium-ion batteries, Congress should establish a tax credit for the purchase of automotive grade batteries for stationary uses. Lithium-ion batteries are suitable for use in stationary applications, but too expensive. Incremental demand from utilities and for other stationary applications could help expand battery supply chains across a number of inputs and could help develop the scale of production needed to reduce the cost of GEVs.

To reach the goals put forward in this report, GEVs will need to become an increasingly significant portion of new U.S. vehicle sales over the next 10 years. Even as battery technology advances, infrastructure is deployed, and consumer attitudes shift, the demands on automotive original equipment manufacturers (OEMs) to retool facilities will be daunting. Currently, the cost to retool an automotive assembly line with an annual capacity of 100,000 vehicles is estimated at approximately $500,000,000. These are non-trivial costs, especially in a time of economic instability. To enable the industry to reach the scale required to deploy electric vehicles in large numbers, additional federal assistance for retooling and other capital outlays will be necessary. Any automotive OEM with U.S. facilities should be eligible.

Finally, as automotive batteries reach the end of their useful life in a GEV, substantial opportunities exist for secondary applications. Enabling consumers to capture the residual value of automotive battery purchases could significantly offset the higher upfront cost of purchasing a grid-enabled vehicle. Unfortunately, the value of automotive batteries for secondary applications is highly uncertain today. This is a sequencing problem: markets for the first generation of used batteries have not developed because there is not a meaningful supply of used batteries, and cannot be until the first generation of batteries used reach the end of their useful life in GEVs. As the first generation of GEV batteries enters the secondary use market, a value will surely be derived. If nothing else, the recycling of battery raw materials alone will generate a notional return on investment for consumers. More likely, battery values will be well in excess of the recycling value as their use in the electric power sector and secondary vehicle markets drive demand. In the meantime, however, markets are likely to undervalue lithium-ion batteries due to their inability to assess the risk of an unknown technology.

Therefore, Congress should authorize the DOE to establish a program to guarantee residual value for large format automotive batteries. Compared to the uncertainty of battery research and development, establishing a minimum residual value would effectively buy down the cost of batteries immediately. Moreover, while the ultimate cost of such a program is dependent on the actual residual value of batteries, may not impose any meaningful costs on the government, if the actual residual value is higher than the minimum guarantee.

VII. CONCLUSION

Transportation electrification offers the most promising pathway to a more secure energy future, but there should be no mistaking the magnitude of this undertaking. The existing oil infrastructure spans the globe, was created over the course of a century, and is worth trillions of dollars. Replacing it with an alternate infrastructure that delivers similar functionality will take decades, which should not be surprising given that new cars routinely last for fifteen years and new power plants are built to operate for fifty years or more.

Without committing to electrify at least parts of our transportation system, the burdens of oil dependence on our economy and our national security are only likely to grow. In the past, we have failed to commit to a particular technology path, whether because of uncertainty as to the correct path or discomfort about the government making such critical decisions instead of the marketplace. That approach has not worked.

A careful examination of the relative merits and pitfalls of each technology has demonstrated not only that electrification offers numerous advantages over oil, and that it has many advantages over the other most promising alternatives, but that none of the other alternatives even offers the promise of a viable solution. We have chosen electrification of the vehicle fleet because we believe that it will work and because we are certain that the alternatives, including maintaining the status quo, will not.

Once this is understood, the nation can commit itself to solving those challenges that must be addressed for electrification to work and to ultimately connecting the nation's light-duty fleet to the electrical power grid. In our estimation only this can close the chapter of U.S. dependence on foreign oil.

Discussion of the Benefits and Impacts of Plug-In Hybrid and Battery Electric Vehicles

Electric Power Research Institute

DRAFT

Massachusetts Institute of Technology – Energy Initiative
The Electrification of the Transportation System: Issues and Opportunities

Introduction

The purpose of this paper is to facilitate the discussion of transportation electrification by providing a broad summary of the design, performance, and cost implications of different plug-in electric vehicle (PEV[1]) configurations. The paper also briefly discusses the electric system impacts and environmental characteristics of PEVs.

The modeling results presented in this paper are a summary of a comprehensive multi-year analysis conducted by the Electric Power Research Institute (EPRI) and Argonne National Laboratory (ANL). The results presented here, including vehicle performance, energy economy, and cost are meant to outline some of the differences and trade-offs between PEV configurations for the purposes of discussion—not to declare conclusively the cost or performance superiority of one powertrain architecture or vehicle configuration over another.

Finally, this paper will briefly discuss to of the key parameters—battery cost and energy economy ration—that are crucial to a complete and accurate understanding of the potential benefits of PEVs relative to other advanced vehicle technologies.

1 Plug-In Vehicle Modeling and Analysis

EPRI and ANL have been investigating advanced, plug-capable, vehicle technologies. This investigation sets out to design and test a broad array of advanced technologies to weigh the consumer acceptability of the proposed vehicle in monetary terms.

A midsize vehicle was selected as the vehicle chassis to base the comparison. Several architectures with varying electric drive capabilities were designed for comparison on the midsize vehicle glider. Common

[1] PEV – Plug-in electric vehicle, typically meant to include the entire family of grid-rechargeable vehicles, including plug-in hybrids (PHEVs), battery electric vehicles (BEVs or EVs), and extended range electric vehicles (EREVs).

design criteria were used to design the vehicles. The architecture includes conventional (CV), pre-transmission (pre-tx), power-split (split), series, and full-electric (EV). The hybrid architectures were designed with electric only capabilities on the Urban Dynamometer Driving Schedule (UDDS). The vehicles under consideration are defined by the shaded vehicles in Table 1.

Table 1 – The vehicle design matrix: Filled cells mark vehicles under consideration.

	UDDS Electric Only Range [miles]					
Vehicle Type	**HEV**	**10**	**20**	**30**	**40**	**100**
Conventional						
Pre-Transmission HEV/PHEV	■	■	■			
Power-Split HEV/PHEV	■	■	■			
Series PHEV					■	
Series EREV			■	■	■	
EV						■

This paper describes the design results, some drive schedule characterizations, and upfront cost estimates for the latest vehicle and schedule test set.

Brief background on several vehicle design and cost modeling topics are provided.

1.1 Defining Vehicle Technologies

Understanding and comparing currently available vehicle technologies requires some basic knowledge of vehicle degree-of-electrification (DOE), vehicle architecture, and general control strategy classifications. Designating the DOE enables the comparison of electric drive capability relative to the total drivetrain power. This relative designation is used in comparing vehicle performance, energy use, and related lifecycle costs between different vehicle architectures. The vehicle architecture describes how the components of the drivetrain are arranged, and as a result, how engine and/or motor power are delivered to the wheels. In turn, the control strategy is a decision-making protocol for how and when components operate.

1.1.1 Degree-of-Electrification

The Degree-of-Electrification (DOE) is used to measure the dominance of the electric drive system (EDS) relative to total drivetrain power. A bulk DOE is often defined for a vehicle design based on component label specifications.

The bulk DOE is a fraction between 0 and 1. Vehicles with DOE=0 are conventional vehicles. Vehicles with DOE=1 are electric vehicles. DOE values in between represent mild HEVs through EREVs.

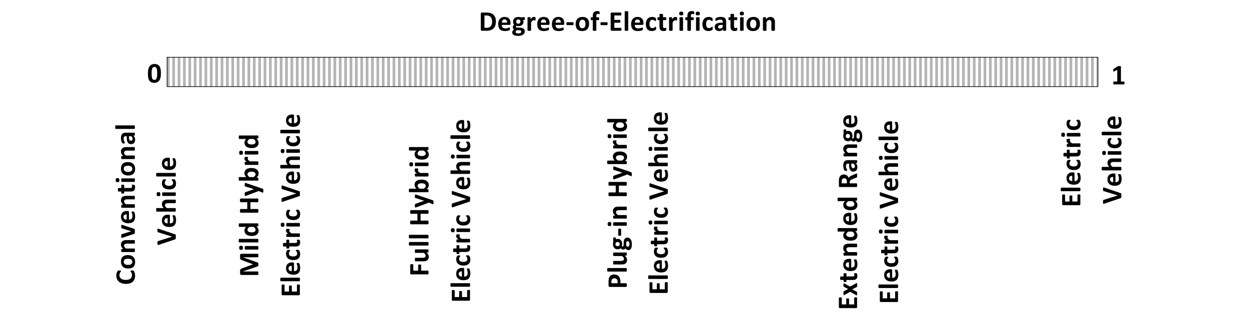


Figure 1 – Degree-of-Hybridization with relationship to HEV classifications.

This metric is defined as the amount of power that can be delivered by the electric drive system normalized by the sum of power available from both the electric drive system and the internal combustion engine.

$$DOE = \frac{P_{ED}}{P_{ED} + P_{EG}} \qquad \textbf{Equation 1}$$

P_{EG} is the engine power. For a given engine design, maximum engine power available is limited by the engine speed: $P_{EG} = f(\omega_{eg})$.

P_{ED} is defined as the minimum of power available from the electric motor or energy storage system (ESS). If electric drive system is limited by the battery power, P_{ED} will change as the battery State-of-Charge (SOC), temperature (Θ), and other operational states: $P_{ED} = f(\mathrm{SOC}, \Theta, \ldots)$. If the electric drive system is limited by motor power P_{ED} will depend on the motor-controller temperatures, and motor speed: $P_{ED} = f(\Theta_{mc}, \omega_m, \tau_m)$. Given that these values vary with time, the DOE will also vary with time[2].

A basis for equivalence between the electric drive and engine power should be identified. How this equivalence is determined will depend on the given vehicle architecture. The engine power rating is evaluated as the power delivered to the engine crankshaft. This power is usually delivered to the remainder of the drivetrain just upstream of a transmission. The battery electrical power must first be delivered to an electric motor to be converted to mechanical power. The mechanical power delivered by the electric motor may or may not be delivered at a location equivalent to where the engine delivers power.

As a bulk measurement, fixed parameters are chosen to calculate a representative DOE. In this investigation these fixed parameters include engine peak power, motor peak power, and battery 10

[2] A DOE time series could be generated for a given drive trace. The time series can then be used to determine propulsion and braking DOEs to produce a metric that considers both hardware and controls implementation for a given driving schedule.

second pulse power at 20% SOC. The battery power is de-rated by a battery to motor-mechanical efficiency of 90%[3]. This bulk DOE is similar to the degree-of-hybridization used by previous research[4].

1.1.2 Vehicle Architectures

Vehicle architectures are defined by the available components and how they are arranged. The main components under consideration are the internal combustion engine, electric motors, and transmission. The following discussion uses a common set of acronyms and schematic elements. These acronyms and elements are summarized here for reference (Figure 2).

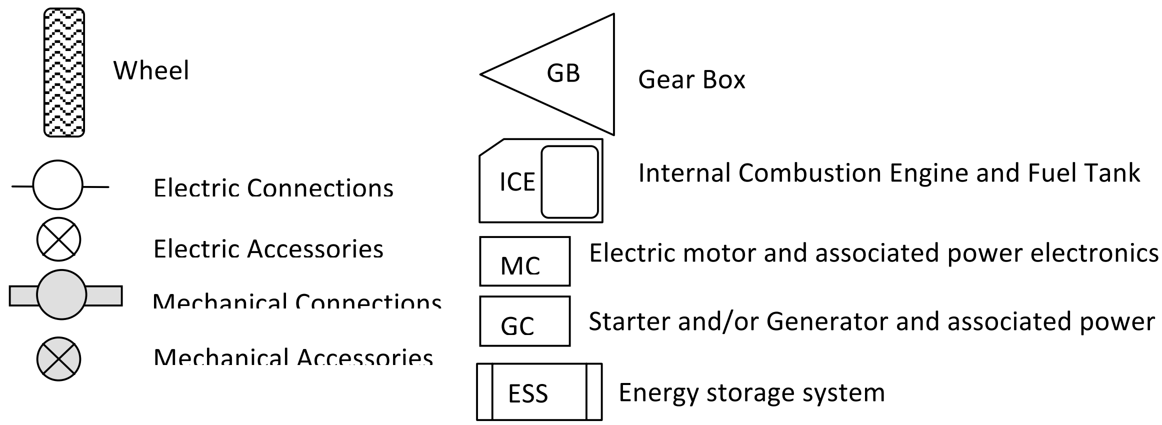
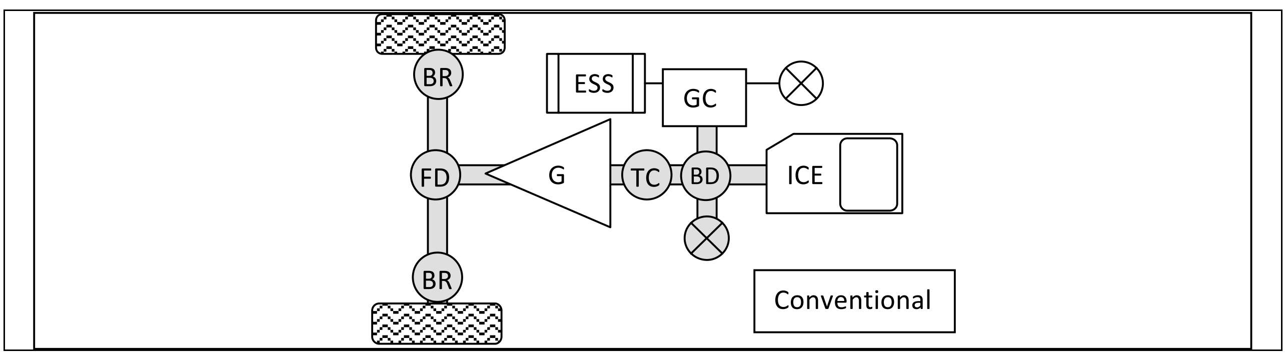


Figure 2 – Vehicle architecture diagram element definitions.

The conventional vehicle has a DOE=0 at all times. Although an electric motor is used to start the engine, the motor is not designed to provide traction power. The electrical system is restricted to engine start and auxiliary loads and is often not rated more than a couple kW (Figure 3).



[4] Santini, D.J., A.D. Vyas, J. Moore, and F. An, 2002, "Comparing Cost Estimates for U.S. Fuel Economy Improvements by Advanced Electric Drive Vehicles," EVS-19 Conference, Busan, Korea, October 19-23.

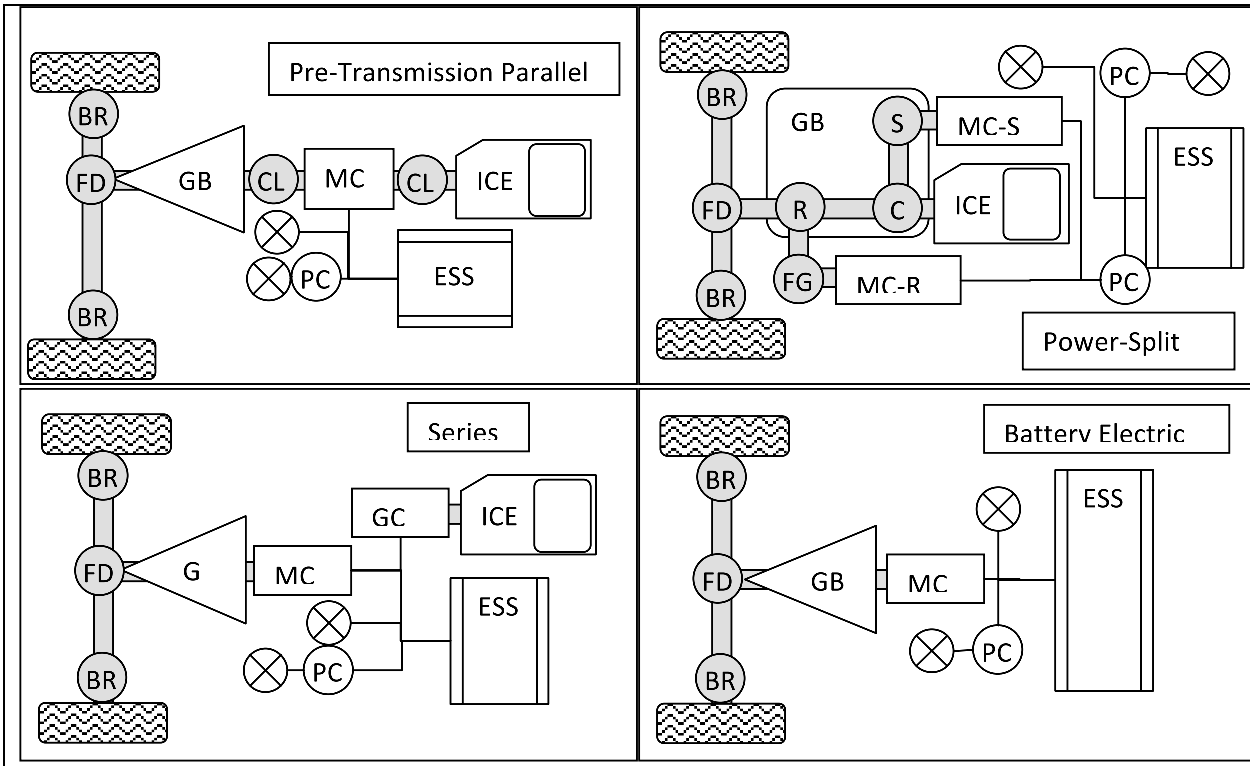


Figure 3 – Vehicle architecture topology. Additional Notes: CL – Clutch, TC – Torque Converter, PC – Power Converter.

The conventional vehicle represents the baseline for comparison. The design is relatively simple consisting of an engine, gear box, driveline components, and accessory systems. Several conventional vehicle design deficiencies are accounted for through vehicle electrification. These deficiencies include: idle operation, full mechanical braking, and engine over-sizing[5].

The parallel HEV architecture describes a component topology where the ICE and electric drive system work together on a common driveline. The dominant parallel system configuration is the pre-transmission (pre-tx). Some have proposed designing very mild pre-tx HEVs by essentially increasing the power rating of the conventional vehicle's GC and ESS to allow for engine start/stop and limited regenerative braking[6]. Higher DOE, mild hybrids have been on the market in the United States since 1999. These mild hybrids allow engine start/stop, regenerative braking, and engine down-sizing[7]. Stronger pre-tx vehicles have yet to be introduced into the general market. The advantages of a moderate DOE pre-tx vehicle are explored. The main advantage of the pre-tx over the remaining hybrid architectures is the use of one electric motor significantly decreases the vehicle's upfront cost[8, 9].

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[5] M. Ehsani, Y. Gao, S.E. Gay, and A. Emadi. (2005) *Modern Electric Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*. CRC Press. ISBN:0-8493-3154-4

[6] J.E. Walters, R.J. Krefta, Ga. Gallegos-Lopez and G.T. Fattic (2004). *Technology Considerations for Belt Alternator Starter Systems Society of Automotive Engineers Technical Paper*: 2004-01-0566

[7] A.Rousseau, B.Deville, G.Zini, J.Kern, J.Anderson, M.Duoba (2001). *Honda Insight Validation Using PSAT.* Society of Automotive Engineers Technical Paper: 01FTT-49

[8] M. Duoba, H.Ng and R.Larsen (2001). *Characterization and Comparison of Two Hybrid Electric Vehicles (HEVs) – Honda Insight and Toyota Prius.* Society of Automotive Engineers Technical Paper: 2001-01-1335

The power-split architecture allows ICE power to be transferred through both parallel and series channels. In practice, and in our simulation, the parallel pathway dominates. A planetary gear set is used with two electric motors to provide electric continuously variable transmission (eCVT) capabilities[5,8,9].

The series architecture requires that power from the internal combustion engine be converted to electricity before being converted to mechanical power by the electric motors. The need to convert engine power to electricity makes the electric drive system in series with the engine relative to the wheels. The excess conversion forces lower engine to wheel efficiencies. However, the engine can be controlled with complete independence from vehicle speed[5]. This study explores a PHEV40 and an EREV-20, 30, and 40 based on the series architecture. The primary difference between the PHEV and EREV is the required battery power.

The electric vehicle by definition has a DOE=1 - electric drive exclusive. The type of GB used in the series or electric vehicle architecture will depend on the capabilities of the MC. A fixed gear-reduction can be used when the maximum MC speed limit is not exceeded at the desired top-speed, and when sufficient low-speed torque can be produced to meet performance requirements[5].

1.2 Vehicle Design

The methods used to design the vehicles are based on multiple performance requirements and design philosophies. Conventional and electric vehicles are constrained in their component selection and sizing as a result of their architectures (e.g. the conventional vehicle is reduced to an engine sizing problem while the electric vehicle is reduced to an electric motor and battery sizing problem). Pre-transmission, power-split, and series vehicles have much greater flexibility in component sizing.

The design method employed evolved over several iterations of vehicles. The chosen method sought to maximize the reuse of base vehicle components across a given architecture. The vehicle with greatest DOE or UDDS electric only range was sized using an Electric-Drive-Limiting (EDL) strategy. The resulting motor, engine, and transmission were reused in the lesser battery-energy vehicles. This strategy resulted in an EDL design for the primary vehicle and designs somewhere in-between EDL and Minimal-Engine-Limiting (MEL) design for the lesser vehicles.

The MEL is not represented in the current version of test vehicles. However, the concept is important to keep in mind when considering the vehicles presented. MEL designs are based on the objective to minimize the specified engine power subject to continuous power requirements. The MEL vehicle's electric drive system is then sized for acceleration or electric only drive capabilities. The MEL design represents an inverse to the EDL design method. The EDL and MEL design methods converge as the electric drive requirements approach EREV requirements.

EREV design methods force electric drive systems to meet a majority of the design requirements – acceleration and top-speed. The EREV design strategy is an EDL design strategy where the electric drive system is constrained to meet the design constraints.

[9] Graham, R. et al. (2001). *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*. EPRI TR-1000349. July

Design requirements were used to design the test vehicle set. The requirements are defined by acceleration, top-speed, and grade-ability performance. Three binding acceleration performance requirements were chosen: 30mph to 60mph, 0mph to 60mph, and 50mph to 80mph acceleration (Table 2).

Table 2 – Acceleration requirements

Acceleration Period	Requirement	Notes
0mph to 60mph	9 seconds	Stop to highway speed acceleration
30mph to 60mph	6 seconds	low speed passing acceleration
50mph to 80mph	9 seconds	high speed passing acceleration

These acceleration constraints yield a moderate- performance vehicle by today's standards. The requirements exceed many of the acceleration ratings of dedicated HEVs from 1997 to 2009. Additional non-binding acceleration requirements were selected for the 0 to 90mph and 0 to 110mph accelerations. These acceleration times were 25 seconds and 35 seconds, respectively.

Vehicles designed to drive on electricity only over the full range of power demands (e.g. EV and EREV) were given a lower top-speed requirement than vehicles that were designed to operate in blended mode during high power demand operation. The EV and EREV were designed with a top-speed of 90mph while the remaining vehicles were designed with a top-speed of 110mph. This difference is argued to limit the continuous power requirements for the EV and EREV vehicles.

Grade-ability is tested by running the vehicle for 20 simulated minutes at 65mph at a 6% grade. The vehicle is run with a low initial battery state-of-charge to ensure that charge-sustaining operation will be observed. Additional mass was added to the vehicle to simulate a fully occupied vehicle. The added mass was selected to be consistent with a given vehicle class and across the architectures by determining the added mass for the conventional vehicle and using that mass for the remaining architectures.

Following design and verification the vehicles could follow LA92 and US06, the vehicles were subject to a broad drive schedule set to sample performance over a broad schedule average vehicle speed. The schedules were classified into certification and real-world. The schedules and their distance, average - speed and acceleration are listed in Table 3. The shaded rows represent certification cycles. The remaining rows are regarded as real-world.

Table 3 – Schedules used for vehicle energy characterization.

					Average Accessories Energy Intensity [Wh/mi]			
					Conventional		HEV / PHEV / EREV / EV	
Schedule name	Average Speed [mph]	Cycle Distance [mi]	Average Accel. [m/s^2]	Average Decel. [m/s^2]	Mech.	Elec.	Mech.	Elec.
NYCC	7.05	1.17	0.617	-0.602	140	170	0.00	291
Artemis Urban	10.9	2.78	0.732	-0.791	91.4	111	0.00	189
ECE	11.3	0.630	0.749	-0.749	17.7	44.3	0.00	56.0

J1015	14.1	2.59	0.569	-0.647	14.2	35.5	0.00	44.9
UDDS	19.6	7.45	0.505	-0.578	10.2	25.5	0.00	32.3
NEDC	20.9	6.84	0.594	-0.788	9.60	24.0	0.00	30.3
SC03	21.7	3.58	0.502	-0.604	45.8	55.4	0.00	94.8
LA92	24.6	9.82	0.673	-0.754	40.3	48.8	0.00	83.5
EUDC	36.7	4.32	0.378	-0.926	5.50	13.6	0.00	17.2
Artemis Extra Urban	37.5	10.2	0.482	-0.498	26.5	32.0	0.00	54.8
US06	48.0	8.01	0.670	-0.728	20.7	25.0	0.00	42.8
HWFET	48.3	10.3	0.194	-0.222	4.10	10.4	0.00	13.1
US06 500	54.0	7.51	0.490	-0.554	18.4	22.2	0.00	38.0
Artemis Highway	61.8	18.35	0.426	-0.509	16.1	19.4	0.00	33.2

The vehicles were subject to constant average accessory loads. The loads differed depending on whether the schedule under consideration was certification or real-world. The conventional vehicle was subject to a mechanical and electrical load of 200W and 500W, respectively, on the certification cycles and 993W and 1200W, respectively, for real-world. The remaining vehicles were subject to electrical accessories of 632W certification and 2054W real-world.

1.3 Cost Modeling

As mentioned previously, there is an economic bias toward ICE power in vehicle design due to the smaller up-front cost of providing additional ICE power, and thus mild hybrids designed by the EDL method tend to be more favorable. This is completely understandable from an economic perspective, since adding additional electric drive capability to an HEV or PHEV necessitates a large motor, battery, and power electronics and proportionally greater cost for each. However, for a vehicle with a sufficiently large DOE (e.g. > 30%), the marginal cost of increasing electric drive capability is relatively less expensive. Though Anderman has argued that batteries larger than those required by say, a PHEV-20 for example, would be too heavy and expensive for mass marketing (e.g. Walsh, 2007), this is far from being an industry-wide consensus, as the benefits of increasing DOE beyond a PHEV-20 are greater relative to the incremental cost, though the exact nature of value and payback will depend upon actual vehicle use.

Large electric motors are commonly used in industrial applications, and thus their costs tend to be more stable and predictable than for batteries, not to mention considerably lower for a given DOE. Additionally, the power rating for automotive-grade electric motors has been increasing steadily with the growing HEV industry, which would seem to imply that their costs are becoming less sensitive to size effects (i.e. $/kW). This would seem to follow well from prior assessments, where small-scale motor costs could be as high as $200/kW (Lipman, 1999), dropping to well below $20/kW at large-scale production (Alexander et al., 2007). Motor costs are assumed to follow functionally with continuous power: $C_{EM} = f\,(P_{cont})$.

Power electronics/inverters also add significantly to electric drive costs, and may include the added costs of distributed control, monitoring, and management of the electric drive system. A significant challenge in estimating and comparing the costs of vehicle power electronics for different vehicle DOE lies in the designation of how these costs are lumped together. For example, some vehicles may integrate motor and battery charge control into a single unit, and thus cost cannot easily be attributed to either motor or battery, respectively. To allow for variability in component designation, it can be useful to consider a range of costs in order to accommodate flexible component boundaries. The power electronic costs are assumed to follow functionally with peak power: $C_{PE} = f\,(P_{peak})$. The parameter estimates for all component cost functions are provided in Table 4.

Table 4- Parameter values for component-level cost functions.

Component	Dependent Variable (Units)	Linear Multiplier	Fixed Added Cost
V6 Engine	Peak power (kW)	11	693
IL4 Engine	Peak power (kW)	12	424
5-spd Automatic	Peak power (kW)	3	300
DCT	Peak power (kW)	3	400
eCVT	Peak power (kW)	3	350
Single speed	Peak power (kW)	1	80
Electric Motor	Cont. power (kW)	14	190
Power Electronics	Peak power (kW)	7	165
Battery Modules	P/E (1/hr)	11	211
Battery Hardware	Nom. Energy (kWh)	10	600
Battery Cooling	Nom. Energy (kWh)	3	90
Engine Support	Peak power (kW)	1	290
EM Cooling	Peak power (kW)	1	70
Light-weighting	Delta mass (%)	-50	9,955

OEM and dealer mark-up costs are calculated as a percentage of the vehicle production cost. The OEM overhead is estimated to be 35% of the powertrain manufacturing cost and OEM profit is 6.5% of manufacturing and overhead. Dealer profits are assumed to be 12% of the cost to the OEM, while a standard mark-up of 1.5 is applied to the glider cost and is assumed to be the same across all vehicle platforms. Though OEM manufacturing costs and retail prices should decline over time for all vehicle types, cost cutting potential is not necessarily indicative of real future vehicle prices.

2 PEV Modeling Results and Discussion

The results presented include a vehicle design and upfront cost comparison. Total cost of ownership are still under invetigation

2.1 Design Comparison

The aggregated vehicle design results are presented in a comparative fashion. These results include vehicle weight, component power, battery energy and power-to-energy ratio, and UDDS AER.

2.1.1 Vehicle Mass

The vehicle weight specification includes the vehicle test weight and the gross vehicle weight. A constant 577kg was used to represent additional passengers and cargo to test grade-ability under gross-vehicle mass. . The vehicle component mass distribution is presented for the vehicle test mass.

The conventional vehicle resulted in one of the lightest vehicles, second only to the electric vehicle. The pre-transmission vehicles showed only small increases in vehicle weight compared to the conventional vehicle. The pre-transmission HEV EDL is lighter than the HEV. PHEV vehicles are as expected heavier within increasing electric range. The power-split vehicles are heavier than the pre-transmission vehicles. The series and EREVs present the heaviest vehicles out of the group. This weight is due to the use of two high power electric motors used in the architecture. The EREVs are the heaviest vehicles due to the increased power demanded from the components.

The glider is a common weight between the vehicles. A common driver and cargo mass is also included.

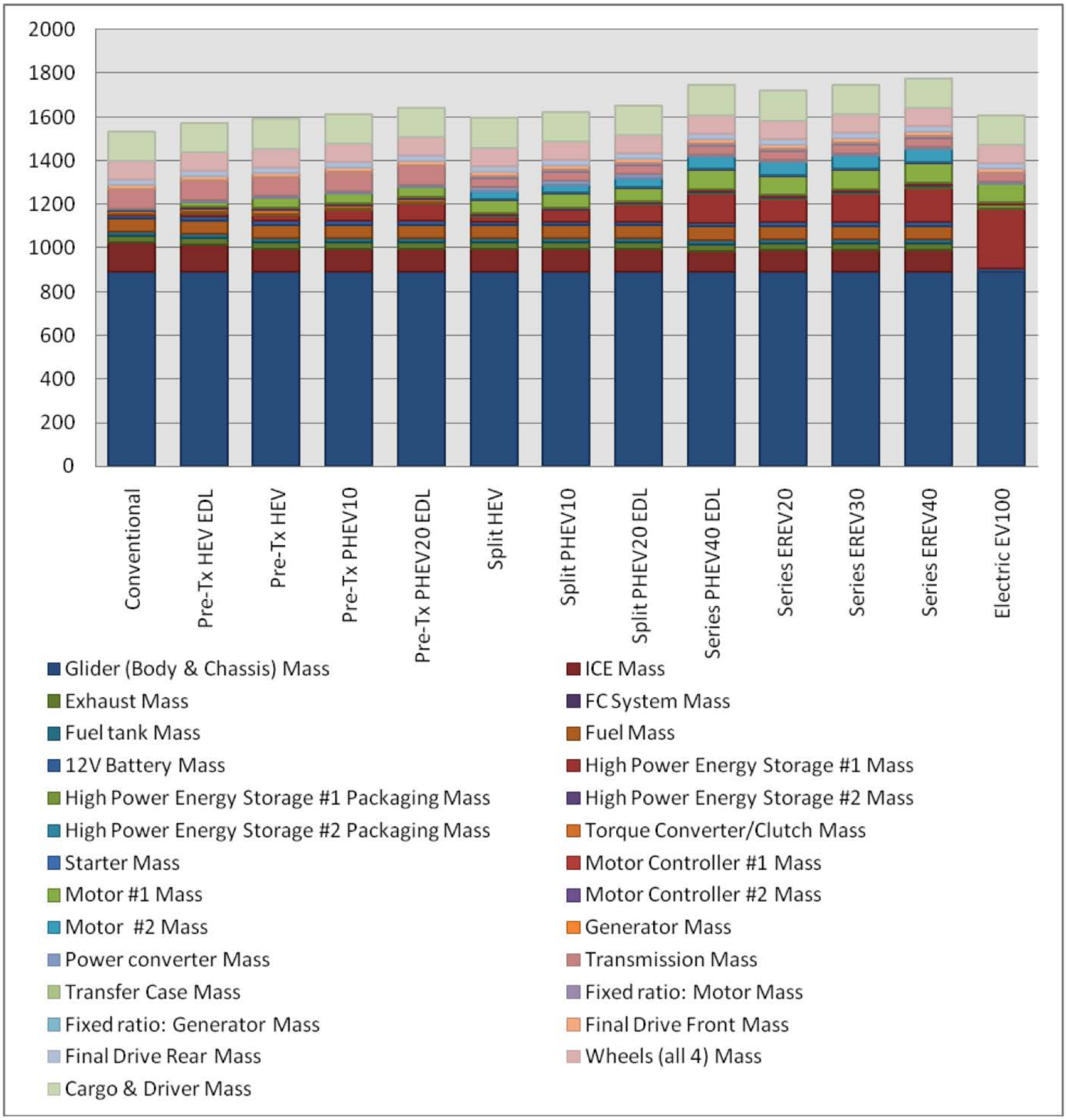


Figure 4 – Vehicle test mass component distribution.

2.1.2 Component Specifications

The component specifications are described by the power rating, battery power, battery energy, vehicle DOH, and UDDS AER.

The component power ratings are compared by observing differences in the trade-off between engine and electric drive power (Table 5).

Table 5- Component power ratings.

Component Vehicle Name	ICE Power (kW)	MC Peak Power (kW)	MC Cont. Power (kW)	MC2/Gen Peak Power (kW)	MC2/Gen Cont. Power (kW)
Midsize Conventional	135	0	0	2	2
Midsize Pre-Tx HEV EDL	120	28	14	-	-
Midsize Pre-Tx HEV	84	54	27	-	-
Midsize Pre-Tx PHEV10	84	54	27	-	-
Midsize Pre-Tx PHEV20 EDL	84	54	27	-	-
Midsize Split HEV	80	76	38	45	45
Midsize Split PHEV10	80	76	38	45	45
Midsize Split PHEV20 EDL	80	76	38	45	45
Midsize Series PHEV40 EDL	70	108	54	68	68
Midsize Series EREV20	75	109	55	73	73
Midsize Series EREV30	75	109	55	73	73
Midsize Series EREV40	75	109	55	73	73
Midsize Electric EV100	-	103	52	-	-

The conventional vehicle required the greatest engine power followed by the pre-transmission EDL HEV. The power-split and pre-transmission HEV and Series EREV20 represent the baseline vehicle platforms for the respective architectures. The pre-transmission used the next highest engine power at 84kW followed by the split and series EREV. The series PHEV40 EDL was able to provide the smallest engine requirement at 70kW given that the EV requires no engine.

The variations in the engine power are the result of several considerations. These include electric assist capabilities transmission shifting dynamics and design strategy. The conventional vehicle has no electric assist and suffers from the shift interruptions of the automatic discrete gear transmission. The pre-transmission architectures also suffer from the torque interrupt of the discrete gear transmissions. Evidence of the discrete gear transmission's impact on engine requirements is demonstrated by comparing the average engine and motor power between a discrete gear and eCVT vehicles during an acceleration test event.

The battery power and energy were used to determine the power-to-energy ratio (P/E). The power used in the calculation is the 10 seconds pulse power at 20% SOC. The energy used is the total nominal energy of the cell. To remain within the P/E domain of the gravimetric energy density parameterized on P/E. This constraint limited the HEV MEL vehicles and forced a larger pack energy compared to the EDL HEVs (Table 6).

Table 6 – ESS beginning and end-of-life specifications for energy and power-to-energy ratio.

Component Vehicle Name	BOL Total Nominal Energy (kWh)	EOL Total Nominal Energy (kWh)	BOL Power-to-Energy Ratio (1/hr)	EOL Power-to-Energy Ratio (1/hr)
Midsize Conventional	0.0	0.0	0.0	0.0
Midsize Pre-Tx HEV EDL	1.3	1.0	25.0	25.0
Midsize Pre-Tx HEV	2.0	1.6	32.5	32.5
Midsize Pre-Tx PHEV10	4.9	3.9	15.8	15.8
Midsize Pre-Tx PHEV20 EDL	9.0	7.2	8.6	8.6
Midsize Split HEV	1.7	1.4	32.9	32.9
Midsize Split PHEV10	5.0	4.0	15.5	15.5
Midsize Split PHEV20 EDL	9.1	7.3	8.5	8.5
Midsize Series PHEV40 EDL	16.9	13.5	4.4	4.4
Midsize Series EREV20	8.4	6.7	22.0	22.0
Midsize Series EREV30	12.4	9.9	15.4	15.4
Midsize Series EREV40	16.3	13.1	12.1	12.1
Midsize Electric EV100	33.2	26.6	5.8	8.3

The amount of energy demanded by the vehicle is forced by the UDDS AER design distance. Satisfaction of this requirement was demonstrated through simulation. Variations in the UDDS drive trace introduced significant sensitivity in distance with changes in pack energy. This sensitivity is due to the driving demand variation presented in the driving schedule.

The component powers allows for an evaluation of vehicle degree-of-hybridization (Figure 5).

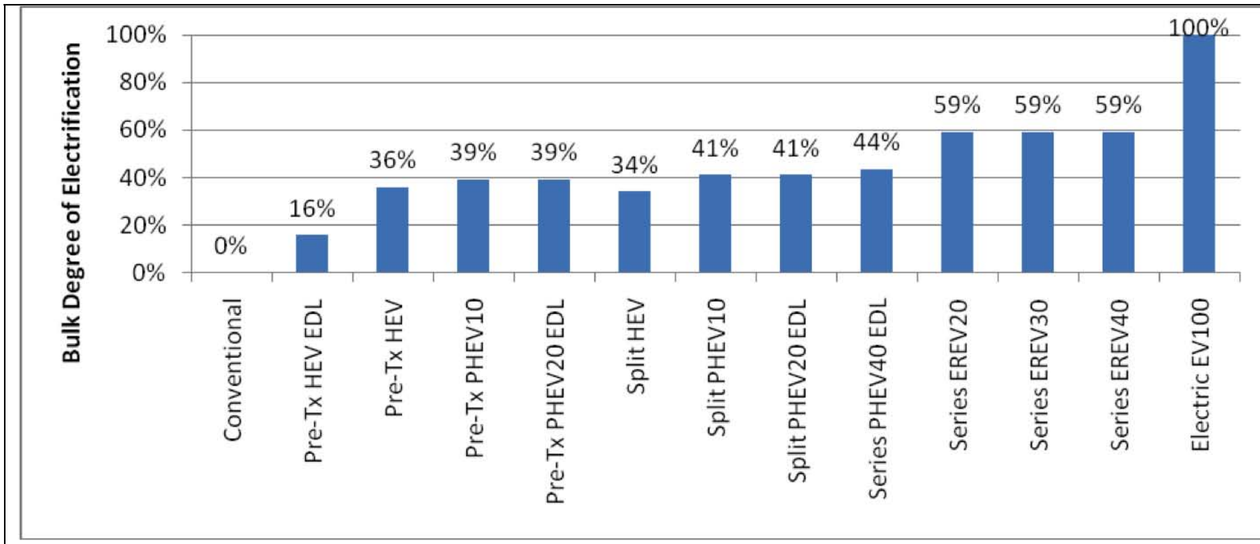


Figure 5 – Bulk Degree-of-hybridization comparison.

The DOE resulting from the vehicle sizing strategies implemented are within the bounds of what would be expected. A conventional vehicle is 0% DOH while the electric vehicle is 100% DOH.

The EDL HEV is in the mild hybrid range with 16% DOE. The pre-transmission HEV and PHEV DOEs are similar – the PHEV10 and PHEV20 are at 39% while the HEV is at 36%. The decrease in the HEV DOE is due to removal of the requirement to meet UDDS in MO mode.

The power-split are subject to a similar trend. The PHEV 10 and PHEV20 are the same DOE at 41% while the HEV is at 34%. The decrease in DOE for the HEV is again due to removing the UDDS CD-AE requirement.

2.1.3 Distance to Depletion

Although UDDS was used to size the CD AE range, the distance-to-depletion for the driving schedules investigated are presented (Figure 6).

The distance to depletion for UDDS is observed to match the design requirements. Although listed in order of increasing average vehicle speed, no clear trend emerges for distance to depletion. The noise observed is due to the variation in accessory loads and degree-of-electrification. The accessory loads on real-world schedules significantly impacts the distance to depletion. A simple comparison between NYCC and UDDS distance-to-depletion illustrates this observation. Further, the DOE will affect the vehicle's ability to maintain electric only operation. Blended operation can significantly extend the distance-to-depletion. This trade-off is observed by comparing the series PHEV20 to the EREV20. The comparison between the PHEV and EREV is subtle. The most dramatic schedule comparison to consider is the higher average speed schedules: US06, US06500 and Artemis Highway..

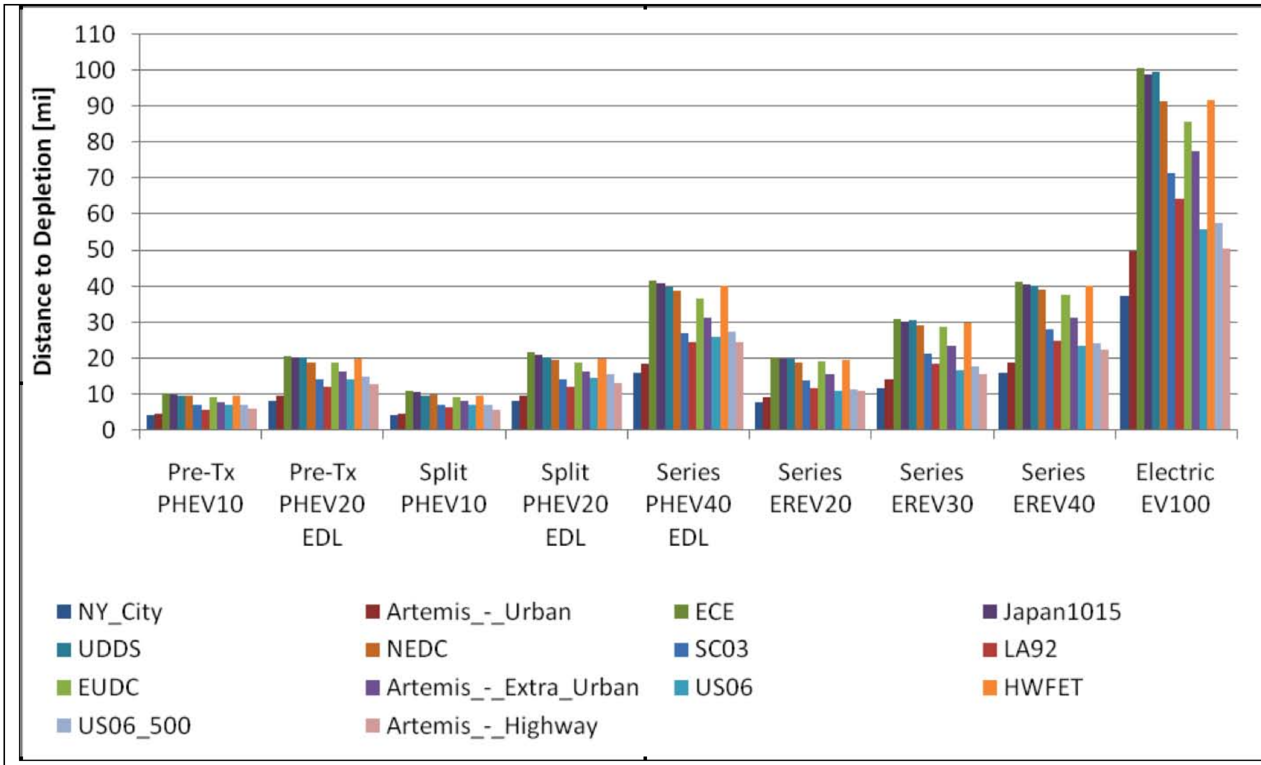


Figure 6 – Distance to depletion versus schedule average vehicle speed.

2.2 Upfront Vehicle Cost

Vehicle cost was estimated for each powertrain technology based on three levels of exchange across the total lifecycle: vehicle costs to the OEM, retail costs to the consumer, and total ownership costs to the consumer. It is assumed that the vehicle is owned for 10 years, has no resale value at end of life, and for those vehicles with plug-in capability, is charged once a day about 90% of the time (i.e. 330 days/yr). Throughput battery charge/discharge efficiency is assumed to be 90%, and off-board charger costs have been added for vehicles with 30 or more miles of nominal electric drive capability. The cost estimates for OEM are presented in Figure 7.

The mark-up from OEM cost to RPE represents the dealers' margin and is estimated at around $6k to $7k per vehicle. The higher cost of the EREV compared to the series configuration is due to larger components specified to meet "full performance" electric drive capability on the LA92 cycle. For the same DOE, the pre-transmission powertrain configuration appears to have a lower up-front cost than that of the powersplit configuration, as shown in previous analysis (Alexander et al., 2007). This difference is due largely to the cost of the transfer case (transmission), which tends to be less complex with fewer moving parts for the pre-transmission configuration.

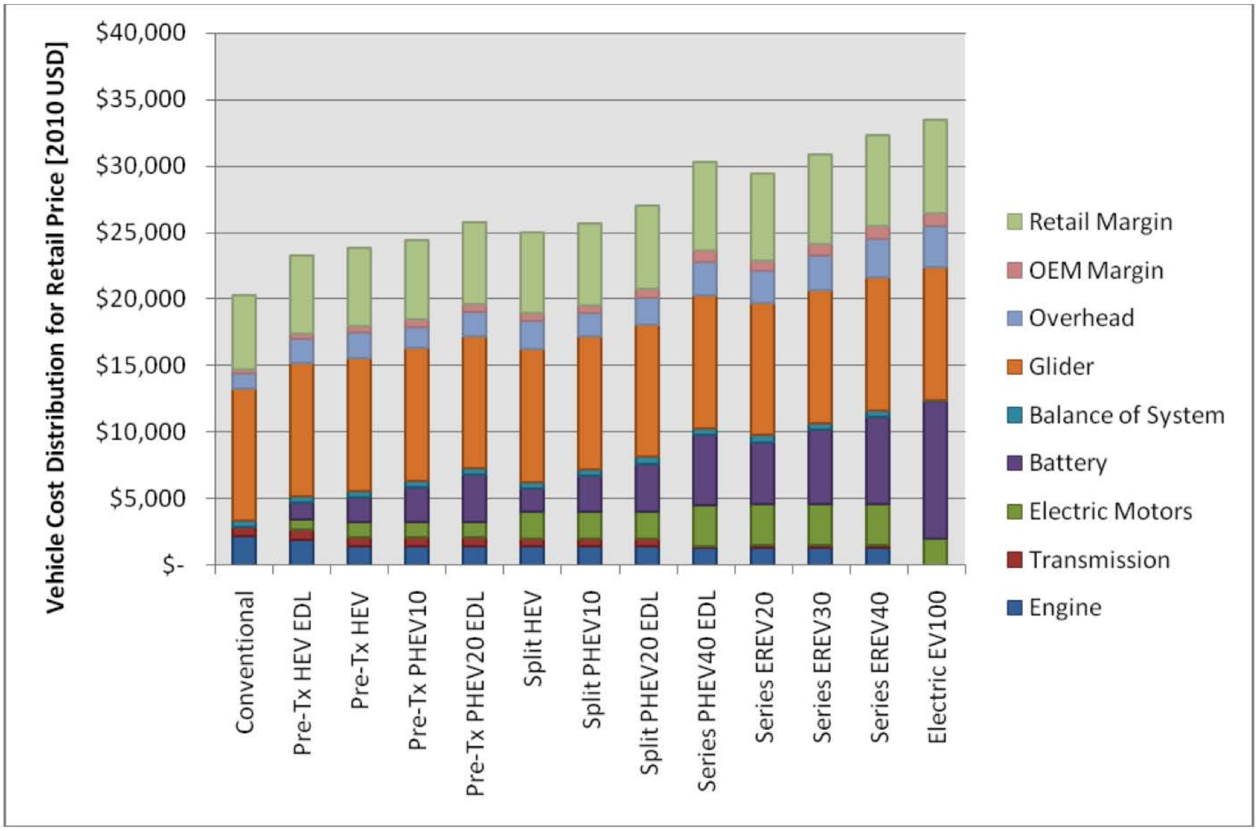


Figure 7- Vehicle retail cost at baseline manufacturing of 100,000/year.

3 Electric System Impacts of Plug-In Vehicles

With plug-in electric vehicles poised to enter the automotive market this year, a remaining concern for electrical distribution utilities is how to account for these loads in their planning process. Seamless integration of plug-in electric vehicles (PEVs) to the grid is a critical step to encourage utility support for PEV commercialization. While technological barriers concerning PEVs continue to fall, the expected influence of PEVs on the electrical system has not been completely evaluated. Understanding the causes and relationships between this new load type and the distribution system will provide the ability for utilities to augment the planning process to account for any additional stresses to their systems.

The total penetration level and the local concentrations of electric transportation vehicles is the key factor in determining distribution system impacts. The electrical characteristics of chargers, charging profiles, and voltage level are contributing factors to distribution impacts. The design and layout of the distribution will also determine the types of impacts that occur.

EPRI has initiated a multi-year project with 18 utilities to understand PEV system impacts with several utilities in the United States and Europe. The basic premise of this effort is to conduct a comprehensive evaluation of potential distribution system impacts through detailed circuit model analysis. The purpose is to identify, define, and calculate the impact to specific utility distribution systems considering total penetrations as well as localized concentrations.

An analysis methodology was designed to capture impacts to the distribution system while capturing the variable nature of PEV loads. The foundation of the analysis is a detailed electrical model of each feeder with all circuit components represented from the substation transformer to each customer meter served from the feeder. The variation of each aggregate customer demand is modeled as an hourly load shape based on historical measurements such that long-term dynamic simulation of the circuit operation over time can be conducted and validated against historical circuit data. The resulting long-term dynamic model of each circuit is then exercised under different levels of PEV variability according to the developed three stage framework shown in Figure 1. The results from the three analyses can be used separately or in conjunction to provide a complete picture concerning the nature and relationship between PEV loads and system impacts.

3.1 PEV Characteristics and Clustering

It's important to note that even for low overall customer PEV adoption rates, PEV clusters can still occur. Based on system configuration and the assumed customer adoption probabilities, clusters will occur randomly throughout the system for each case. For example, PEV clusters are visible in the daisy plot shown in Figure 2. Each PEV is represented by the circle and as PEVs are introduced at the same location they are spaced in a similar fashion as petals on a flower. Higher penetration rates, of course, increase the potential for larger cluster sizes and more frequent occurrences. While PEV clustering may indicate an increased risk higher than average loading levels, PEV clustering alone does not signify the likelihood of negative impact occurrence as the other PEV load characteristics must also be taken into account.

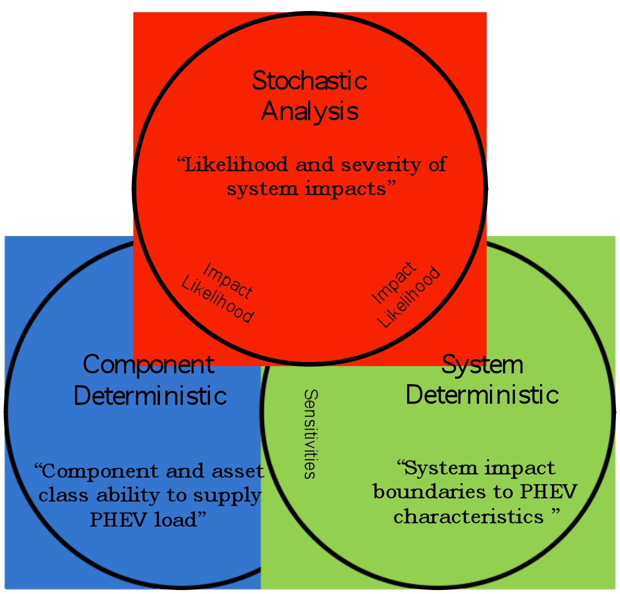


Figure 8
Impact Analysis Framework

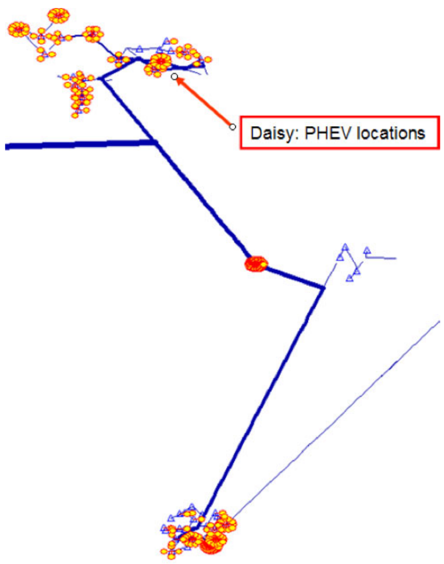


Figure 9.
Example Daisy Plots Illustrating Clustering at 8% Penetration Levels

Given the radial configuration of most distribution circuits, the closer a circuit component is located to the loads the more likely it is to serve a PEV cluster. This relationship is illustrated in Figure 3 which shows the maximum occurring clusters sizes experienced by during the analyses. In this case, cluster sizes are expressed in terms of the ratio between PEVs per customer served. The higher ratio the higher the percentage of PEVs per customer served off that device. As shown, components serving fewer customers experienced higher relative cluster sizes. However, for devices serving large number of customer this PEV/customer ratio converges toward the original customer adoption rate in response to increased diversity in PEV spatial variations.

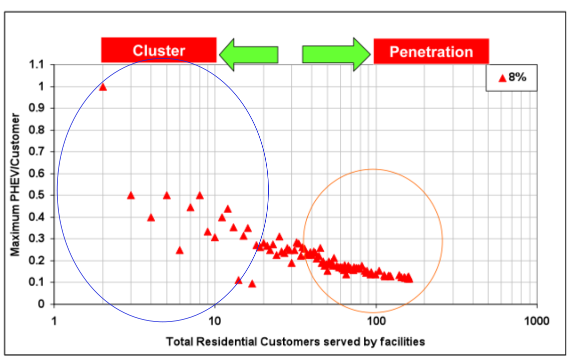


Figure 10.
Relationship between Cluster Size and Customers Served

3.2 Duke Market Assessment and Cluster Study

As part of EPRI distribution impact analysis Duke performed a detailed market assessment to model PHEV adoption, preference of PHEV types, and propensity to charge at night. Duke's market assessment study examines how the adoption of electric vehicles can often cluster within a neighborhood or on a particular street. The methods used in this study were successful in identifying electric vehicle market segments that occur in statistically significant geographical clusters. The results validate an a priori proposition that geographic clustering may occur when overall PHEV penetration is still low. Duke's analysis shows that there is likely to be minor short term risk or reward for electric utilities with respect to electric vehicle adoption, but also that significant long term value or risk exists, depending on how judiciously utilities manage pricing, charging and infrastructure. The margin of difference between profit and loss lies with the extent to which customer adoption is geographically clustered, whether customers demand faster charging times, and how utilities are able to insure optimal charging times are met, relative to existing system utility peak loads. Customer car purchases are likely to cluster geographically within neighborhoods. Customers appear to want fast charging and convenience, albeit within some price tolerance. Figure 4-19 – 3-30 show the capacity load at risk for secondary transformers at individual summer peak and nameplate rating s with additional load from 5, 10, and 20 percent EV penetration.

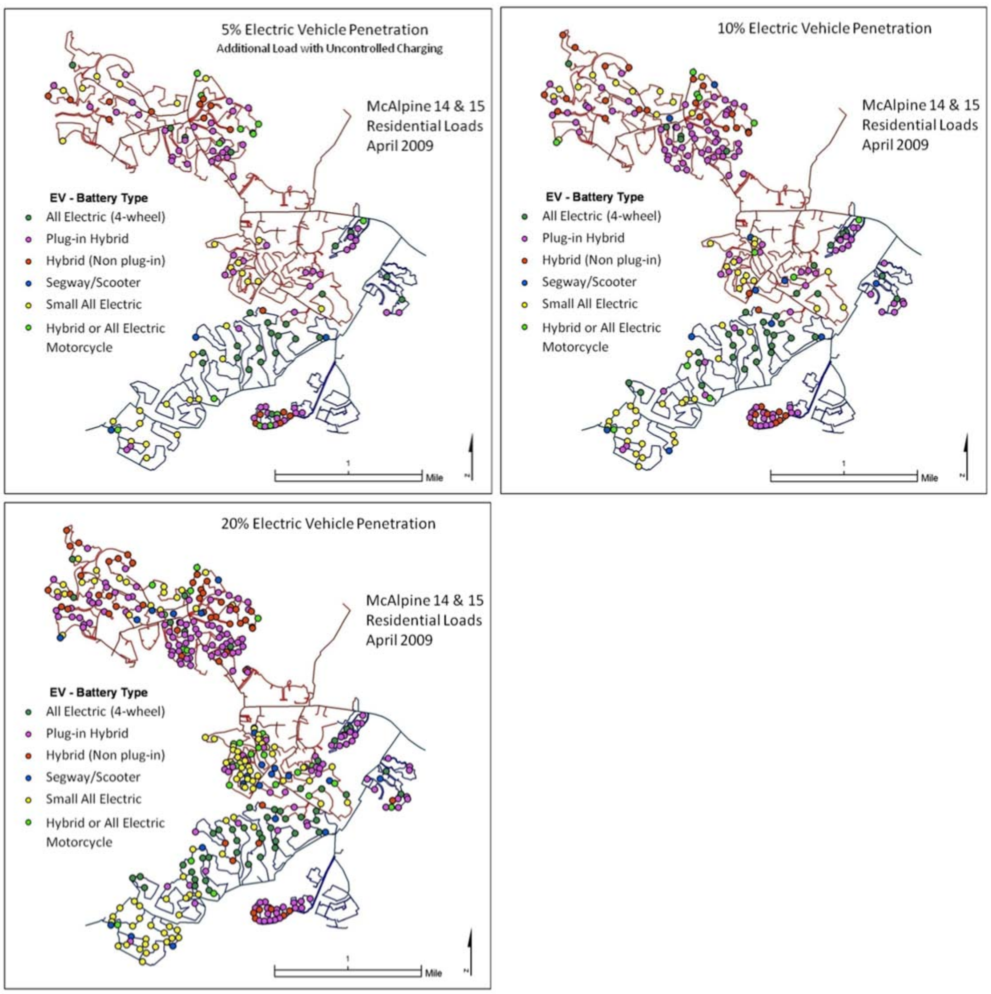


Figure 11

Display of most preferred EV on each secondary transformer for 5, 10, 20% EV Penetration

3.3 Substation Loading Analysis

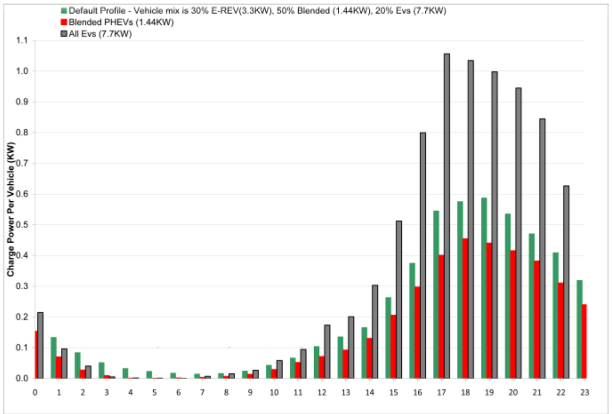
The overall feeder or substation loading in response to PEV penetration is intrinsically dictated by the aggregate make-up of the interconnected PEVs and customer charging habits. Given the Law of Large Numbers, the average response for large scale aggregation of PEV behavior, such as substation loading, will tend toward the mean of the PEV characteristics. For charging based purely on customer driving behavior, the charging patterns seen at the substation will tend to correlate more closely with statistical driving patterns. Furthermore, because the home arrival times tend to correlate with typical peak load times, it is often assumed that vehicle charging could create a large coincident peak. However, the resulting increase to the peak demand may not be as large as sometimes assumed given wide dispersion of home arrival times. Even if it's assumed that drivers immediately charge upon returning home, only about 22% of drivers are expected to arrive home during typical peak hours of 5 and 6 PM. Furthermore, people do not always drive a sufficient distance each day to require multiple hours to fully recharge their vehicle. As such, vehicle charging is likely to be relatively well distributed even for uncontrolled charging.

To illustrate, the average loadings per connected PEV seen at the substation are shown in Figure 4(A) for one of the studied feeders. It was observed that for different vehicle mixes the aggregate on-peak load for a PEV is expected to be between 0.5-1.1 kW per vehicle for this system. Regardless of the composition of vehicles considered, the most dominant factor in the average hourly demand is the expected interconnection times.

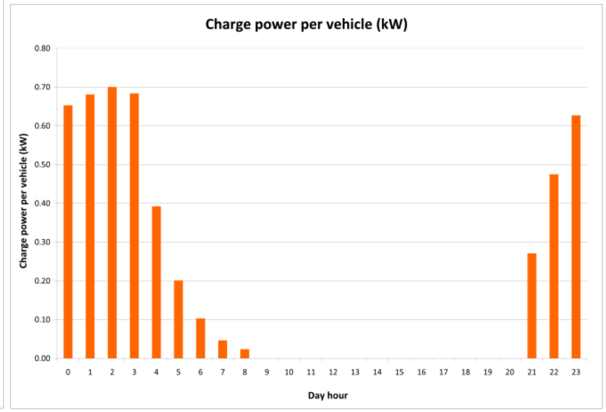
Controlled charging can significantly resolve projected PEV loading impacts to distribution system assets. The aggregate PEV substation loading for a simple control strategy (using the default PEV mix) is shown in Figure 5(B) where the charge is shifted to later hours and evenly distributed over a 6 hour period. This emulates a control where vehicles charging times are staggered between the hours between 9 pm to 3 am. Note that the peak demand remains at about 0.7 kW per vehicle, but now occurs during times where the existing load is typically lower thus improving overall system load factor. Controlled this way, vehicle charging would not require additional generation capacity and would have a relatively small impact. More sophisticated control strategies could potentially reduce the loading impacts even further.

3.4 Asset Thermal Capacity

Indentifying the extent to which particular distribution asset classes may be affected by PEV demand requires first examining how PEVs are expected to be distributed across the feeder. As PEV adoption occurs, the locations of these loads are expected to vary with customer preference, which can appear random to the distribution engineer without some level of market acceptance data. As such, correlating expected PEV demand against the remaining capacity of each asset will provide a strong indicator of the number and type of assets most at risk from PEV adoption. Assets which are potentially at risk of exceeding their thermal ratings due to PEV adoption can be then identified by comparing their existing remaining capacity to the projected PEV demand C_n. The estimate of the demand also permits a confident identification of which assets are unlikely to be impacted.



A

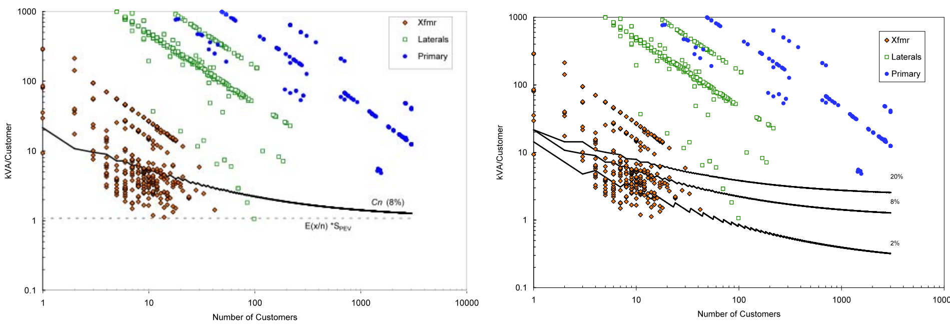


B

Figure 12
A) Aggregate Power Demand for Uncontrolled Vehicle Charging
(B) Average PEV Loading for Customer Behavior with Simple Charge Control

The calculated peak hour remaining capacities for an example circuit are plotted in Figure 5(A) as a function of the number of customers served from the component. Additionally, the estimated maximum PEV demand is also plotted permitting the quick identification of which assets are unlikely to be impacted and those which are at risk of impact. In this example, C_n is calculated for an 8% PEV market penetration and assuming a Level 2 charge profile (240V-30A) for every vehicle. Therefore, at 8% penetration each asset with a remaining capacity falling above the projected demand is unlikely to be impacted by 8% PEV market penetration.

Intuitively, as PEV market penetration increases so does the potential for increased system impacts. The projected maximum demands considering different PEV market penetration levels are plotted in Figure 6(B). As expected, the number of assets falling below the projected C_n line increases as does the penetration level. More importantly for this system, the nature of the asset capacities in relation to the C_n lines clearly indicate the impact from PEV adoption will most likely first appear on service transformers in particular. Not surprisingly, those transformers with the lowest kVA/customer capacity are the most susceptible. It is also interesting to note possibility of impacts from PEV clusters cannot be discounted even for penetrations as low as 2%.



A B

Figure 13
(A) Aggregate Power Demand for Uncontrolled Vehicle Charging
(B) Average PEV Loading for Customer Behavior with Simple Charge Control

It is important to restate that the developed asset evaluations do not identify assets that are likely to become overloaded. Rather, only those assets which are unlikely to be overloaded are identified given a particular PEV penetration level. The remaining assets are clarified as being at risk of exceeding their thermal rating. Assessing the likelihood of overload occurrence requires accounting for all diversity factors such as system load profiles, PEV charge behaviors, as well as temporal and spatial variations.

As design practices varies between utilities as well as specific operating condition between circuits, the actual level of thermal overload impacts is circuit dependent. However in general, assets with low capacities per customer are the most likely to be impacted by customer adoption of PEVs. This is especially true for those assets, such as service transformers, which do not benefit as greatly from PEV load diversity.

3.5 Transformer Insulation Aging

Increasing the load on a distribution transformer will intrinsically increase the overall deterioration or “thermal aging” of the transformer’s insulation. However, the rate of deterioration depends upon a number of factors including the variation in customer load over time, the ambient operating conditions, as well as the thermal characteristics of the transformer. As PHEV charging can potentially alter the nature of customer load profiles, identifying the extent to which PHEV charging influences distribution thermal aging rates is a natural concern. However, evaluating system wide thermal aging requires identifying:

- which assets are at risk from PEV charging,
- the likelihood of thermal aging impacts, and
- conditions under which these assets are at risk.

This information is necessary if specific transformer insulation aging estimates are to be translated into overall system impact. Furthermore, it directs which conditions should be used to evaluate thermal aging relevant to that system. The EPRI PHEV study has been designed to identify these key factors so that subsequent thermal aging evaluations can be performed effectively for each study circuit. The approach to evaluate PEV influence on thermal aging include:

1. **Determine which transformer assets may be potentially impacted.**
   As thermal aging is a nonlinear cumulative process, any increase in aging due to PEV charging will vary based on existing transformer load levels. Those transformers which may exceed their utility specific ratings are especially at risk of meaningful thermal aging impacts.

2. **Determine impact likelihood using stochastic evaluations.**
   Stochastic evaluations are performed which project the likelihood of a transformer overloads in response to both PEV temporal and spatial variations. The stochastic evaluations also designed to identify the specific customer and PEV load conditions under which the transformer's ratings were exceeded.

3. **Perform thermal aging sensitivity analyses in response to PEV loadings.**
   Thermal aging sensitivity analyses can be performed to make qualitative conclusions concerning the nature of PEV influence on thermal aging. Some common questions which can be addressed:

   - Does moving the demand to late evening hours benefit thermal aging?
   - Can PEV charging result in thermal runaway?
   - How does different PEV charging profiles (120V, 240V, etc.) influence thermal aging?
   - What influence of base case loading and ambient temperatures?
   - Which transformer thermal characteristics most strongly influence thermal aging given PEV loading?

4. **Utility specific evaluations of transformer loss of life.**

Once the specific assets and conditions for potential impact on thermal aging have been sufficiently identified, relevant worst-case thermal aging estimates will be performed providing bounds to expected thermal aging impacts. However, in order to perform a meaningful and complete assessment of thermal aging impacts additional utility and feeder specific data is required. In particular,

- Transformer thermal characteristics
- Transformer load and no-load losses
- Hourly load profiles (at the transformer) including daily and season variations
- Hourly ambient temperature conditions

3.6 New York State Grid Impact Study

While the implications of increased penetration of PEVs is being studied generally on a national level and in several more localized regions as part of the multi-utility distribution impact work, the specific impact to New York State has not yet been fully understood. As part of another initiate with NYSERDA and ConEd, EPRI is conducting a comprehensive study to assess the energy, environmental and distribution impacts of PHEVs in New York State. Of particular interest is the impact on Zones J and K, i.e. downstate, due to the concentrated electric demand and vehicle population in those areas. Key aspects of this study include

- Identification of the 'base case' scenario of transmission/distribution capacity assuming no PHEV penetration;
- Identification of several realistic PHEV penetration scenarios, including vehicle characteristics and required load support;
- PEV Distribution impacts on the largest secondary network in Manhattan and another radial circuit in NY
- Implications of V2G applications or utility aggregated load control
    - Literature review of past/current work in vehicle-to-grid (V2G) and the use of aggregate load or distributed generation (e.g. solar PV) to provide peak shaving or load following
    - Implement preliminary simulations of the actual distribution systems with Photovoltaic, energy storage and PEV in OpenDSS software.
        - Benefit from using PEV as controllable energy storage in Distribution Systems.
        - Coordinating Photovoltaic(PV), energy storage and PHEV charging

3.7 Summary

The distribution impacts of PEVs can be summarized as follows:

- **PEV peak demand**
    - Recognizing, all distribution circuits will not realize the same level of PEV adoption, the extent of system impacts depends upon the PEV penetration and charge behaviors of PEV adopters
    - Likelihood of a given system component becoming overloaded is a function of the remaining capacity on the element and the number of customers served from the element that are potential charging locations for PEVs.
    - The increased loading on the substation transformer tends to be tempered by the diversity in charging times for the many PEVs that are served across the entire feeder. Conversely, a single service transformer serving 5-10 customers may become overloaded with 1 or 2 higher charge current PEVs.

- Controlled charging of the PEVs can potentially reduce the loading impacts, but care must be taken to ensure that the control strategy does not create secondary system peaks.
- low capacity per customer ratios combined with low PEV load diversity (assets closer to the customer) are the most likely to be impacted as they do not benefit as greatly from PEV load diversity
- The remaining capacity per customer can be used as a metric for evaluating possible risk of impact due to customer adoption of PEVs
- Stochastic results show that the temporal and spatial diversity of PEVs charging on the system mitigates mass overloads of any particular asset class for penetration levels in the 2-8% range.

- **Anticipating potential PEV overload impact**
  - Load planning based on detail distribution model
  - Transformer load monitoring (direct or via AMI)
- **Potential adjustments to future distribution planning standards**
  - Transformer sizing, customers served off each transformer, transformer thermal ratings

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4 Environmental Assessment of Electricity as a Transportation Fuel

The following analysis was conducted to extend the results of the previous national analysis by the Natural Resources Defense Council (NRDC) and the Electric Power Research Institute (EPRI) to address specific aspects of the regulatory and environmental landscape in California (EPRI 2007a; EPRI 2007b). California has persistent and diverse air quality problems which endanger human health and require aggressive remediation. The California executive and legislatures are also highly committed to reducing greenhouse gas emissions from the transportation and electricity generation sectors. These factors have led to pioneering legislative and regulatory activity to improve air quality and reduce greenhouse gas emissions. Based on recent changes in the national political landscape, similar goals may also be created at the national level, and it is likely that regulations already implemented in California will be seen as potential starting points for similar federal laws. This report investigates the effects of the currently implemented regulations in California on air quality and greenhouse gas emissions.

4.1 Air Quality Assessment Summary

An air quality model was used to simulate the air quality impacts of PHEVs in 2030. The Community Multiscale Air Quality (CMAQ) modeling system created by the Environmental Protection Agency (EPA) was used to simulate both scenarios and air quality impacts were evaluated for ozone mixing ratios, particulate matter concentrations, nutrient (sulfate, nitrate and total nitrogen) deposition, mercury deposition, and visibility.

The results of the analysis suggest that PHEVs offer significant air quality benefits for multiple pollutants (including ozone, particulate matter and deposition rates for sulfur, nitrogen and mercury) in California. In addition, population-exposure and deposition-flux calculations show that the majority of the population and land area of California experience benefits due to the penetration of PHEVs in the vehicle fleet.

4.2 Greenhouse Gas Emissions Analysis Summary

One of the primary anticipated benefits of plug-in hybrid electric vehicles is their ability to reduce greenhouse gas emissions. However, there are expected to be significant changes in the next 40 years in power plant emissions, vehicle performance, and transportation fuels production which will drastically change the embodied carbon content of transportation electricity and the emissions of alternative technologies like advanced hybrids and conventional vehicles using low-carbon fuel. These tradeoffs are especially interesting to analyze in California, which has committed through Assembly Bill 32 to reduce greenhouse gas emissions to 1990 levels by 2020 and to 80% below 1990 levels by 2050. The analysis considers the role of PHEVs in helping to meet these reduction goals by analyzing the simultaneous evolution of the electricity grid, the production of transportation fuels, and the transportation fleet from 2010 to 2050.

A suite of regulations was considered which govern emissions from the electricity sector, emissions from vehicles, and emissions from vehicle fuel production. The regulatory environment in California is highly dynamic and should be expected to change as additional knowledge is gained regarding the feasibility of different recommended paths and the potential for future improvements.

4.2.1 Electricity Production

A full production electricity system production simulation was performed for the time period between 2010 and 2050. Figure 14 shows the generation sources without PHEVs. The Renewable Portfolio Standard (RPS), which requires 20% of generation to come from renewable sources by 2010 and 33% by 2020 led to substantial emissions reductions. Large hydropower and nuclear are not renewable, but are non-emitting, so the combination of new renewable technologies and existing economical non-emitting technologies results in a rapid and extensive shift away from already efficient technologies like combined cycle natural gas.

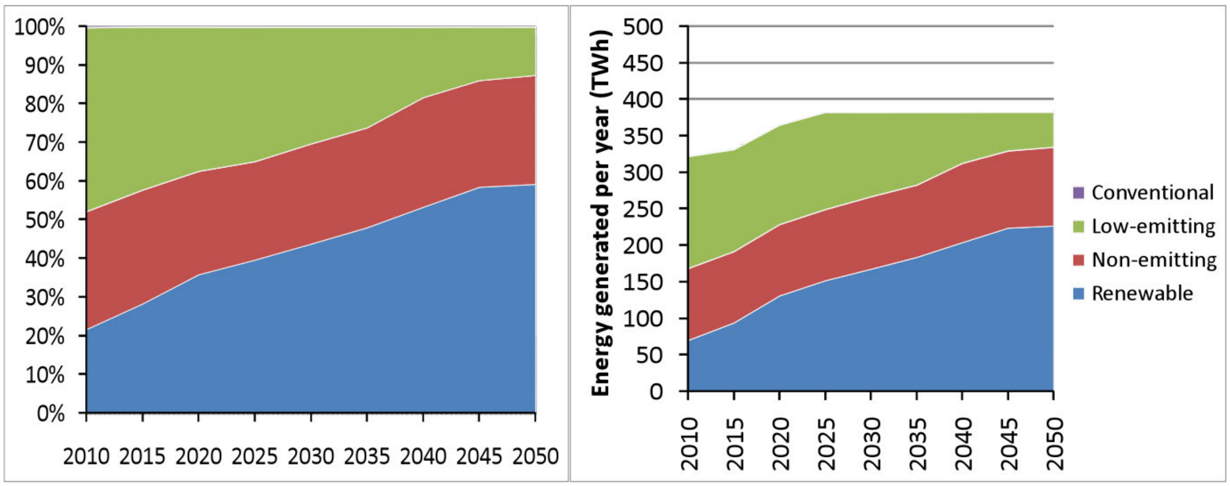

Figure 14
Generation Sources Without PHEVs, Relative (left) and Absolute (right)

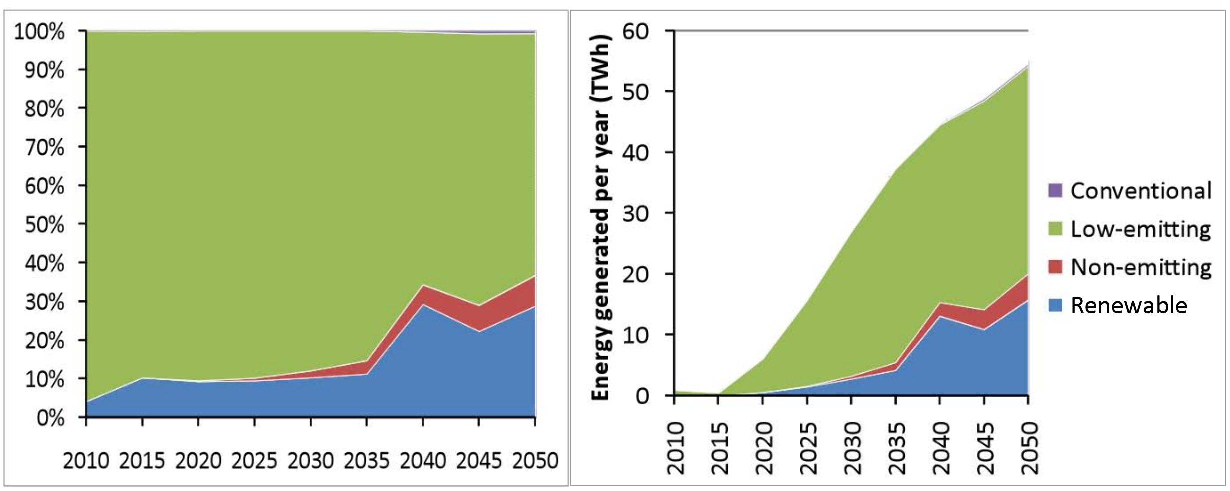

Figure 15
Marginal Generation Sources, Relative (left) and Absolute (right)

4.2.2 Greenhouse Gas Emissions

Figure 15 shows the marginal generation source used to charge vehicles. In general, the generation source is low emitting in the near term with an increasing share of renewables as time progresses. Even with substantial PHEV penetration, the PHEV charging load is relatively small, which makes exactly modeling the constraints of the RPS for PHEVs difficult; renewable electricity does not represent 33% of the electricity used to charge vehicles despite RPS constraints which require this to be the case. This means that analyses of electric transportation carbon emissions are conservative.

Figure 16 shows the integrated emissions of the light-duty transportation sector and the electricity sector for Minimal PHEV scenario and **Figure 16**Figure 17 shows the integrated emissions for the Medium PHEV scenario. The relatively limited progress in the transportation sector has prevented the total emissions reductions from meeting the 2050 AB32 target of an 80% reduction below 1990 levels, which for the two sectors together would be 40.1 MMTons CO_2e. However, increasing PHEV penetration from the minimal amount to a medium penetration reduces CO_2e emissions by 23 MMTons, bringing California much closer to the overall goal. As shown in the figures, combined emissions remain above the 2050 AB32 target. In order to meet the targets, further reductions of CO_2e are necessary, primarily in transportation.

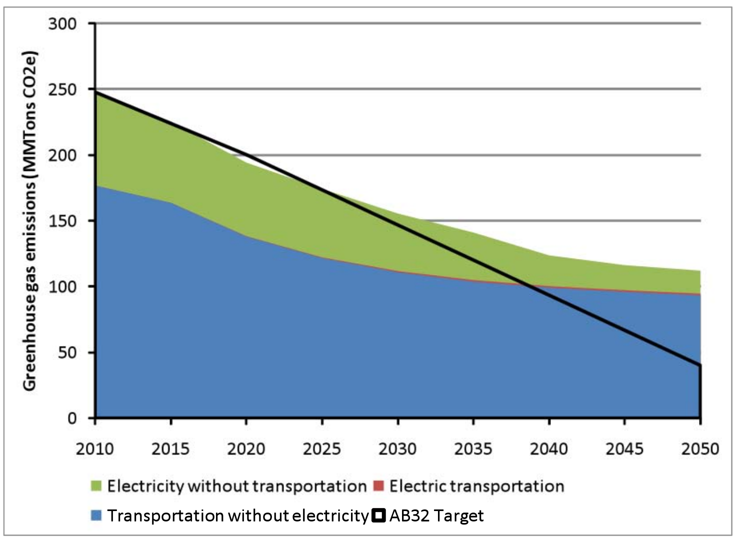

Figure 16
Combined Greenhouse Gas Emissions in the Minimal PHEV Penetration Scenario

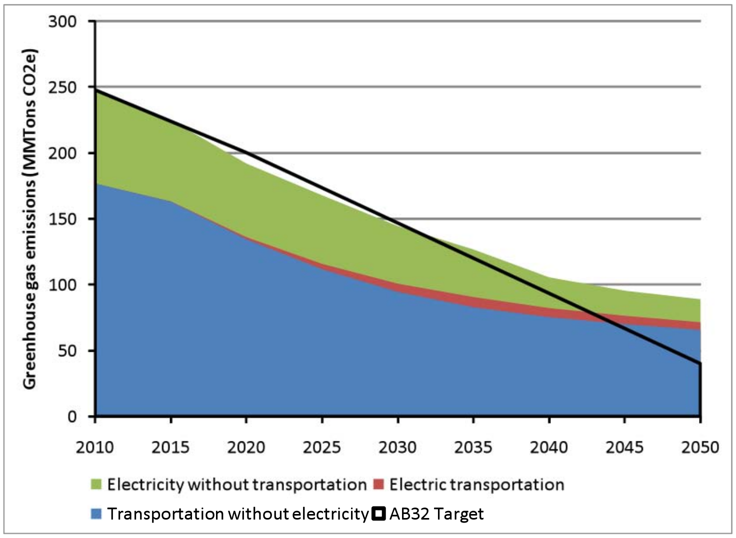

Figure 17
Combined Greenhouse Gas Emissions in the Medium PHEV Penetration Scenario

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5 Key Study Parameters – Battery Cost Assumption and Energy Efficiency Ratio

There have been a number of recent studies which have discussed battery cost estimates, including studies from the Boston Consulting Group (BCG 2010), the National Research Council (NRC 2010), Argonne National Laboratory (Nelson 2009), and EPRI (EPRI,2005). The studies from the Boston Consulting Group and the National Research Council concluded that battery costs would be very high in the near term and would require subsidies to compete in the mid term. This contradicts other studies such as those from Argonne National Laboratory and EPRI, and stated estimates from automotive companies and suppliers. The discussion below describes EPRI's approach to evaluating the results of these studies.

5.1 Battery Cost Estimation

Although battery cost studies can differ in methodology and data sources, there are a number of components which all cost studies should have in order to be representative and verifiable:

- A bottom-up cost model which accounts for differences in chemistry, production rates, and process steps
- Clear, well documented assumptions for component and production costs
- A reasonable production rate given the time period considered
- Discussion of sensitivities to costs which are critical, but difficult to estimate given current information

A bottom-up cost model which accounts for differences in electrode chemistry, production rates, and process steps

Although it is possible to start simple cost models at intermediate levels in the process, electrode chemistry is such an important part of battery construction and use that a model intended for use as a primary reference must start at this level. There are a variety of production processes which must be accounted for, and demonstrating that these are handled correctly is critical in ensuring that the model is sufficiently detailed to estimate current costs accurately and to predict future developments in battery costs.

Clear, well documented assumptions for component and production costs

Clearly documenting assumptions is a critical part of presenting any science-based analysis. Vehicle battery production is immature enough that there are often widely varying assumptions for critical parameters (for example, scrappage rate). These assumptions should be stated openly and clearly so that they can be compared with existing studies and production data.

A reasonable production rate given the time period considered

A common problem in estimating battery costs is assuming that batteries will be built in quantities that are either unreasonably high or unreasonably low. There are a wide variety of vehicle production estimates, especially beyond the near future, but in general a dedicated battery plant will require quantities of 10k – 100k battery packs per year. Immediate evidence does not indicate that additional plant-level benefits accrue above a few 100k packs per year; at this level it is likely that multiple plants would be built.

Discussion of sensitivities to costs which are critical, but difficult to estimate given current information

There are a number of 'wild card' parameters, like scrappage rates, the usable state-of-charge window, degradation margin, and various markups. It is important to quantify which of these parameters significantly affect the final battery cost, what combination of assumptions is used to estimate costs in the mainline estimate, and how likely these parameters are to change as production progresses.

Discussion of battery studies

Error! Reference source not found. shows a comparison of the four studies considered here. In general, it has been difficult to validate the results of the studies from the Boston Consulting Group and the National Research Council.

Table 7
Study comparison

	Bottom-up cost model	**Clear, well-documented assumptions**	**Reasonable production rate**	**Discussion of sensitivities**
Boston Consulting Group	?	No	No	No
National Research Council	No	No	?	No
Nelson, et at / Argonne National Labs	Yes	Yes	Yes	Yes
Kalhammer / EPRI 2005	No	Yes	Yes	Yes

Figure 18 shows the costs from these four studies during the timeframe of each study for batteries for PHEV40 vehicles (the studies which do not have a specific year but are considered 'near term' are shown in 2015). All results are in terms of dollars per usable kilowatt hour. General Motors has stated publicly that current battery costs for the Chevrolet Volt are about 1000 $/usable kWh.

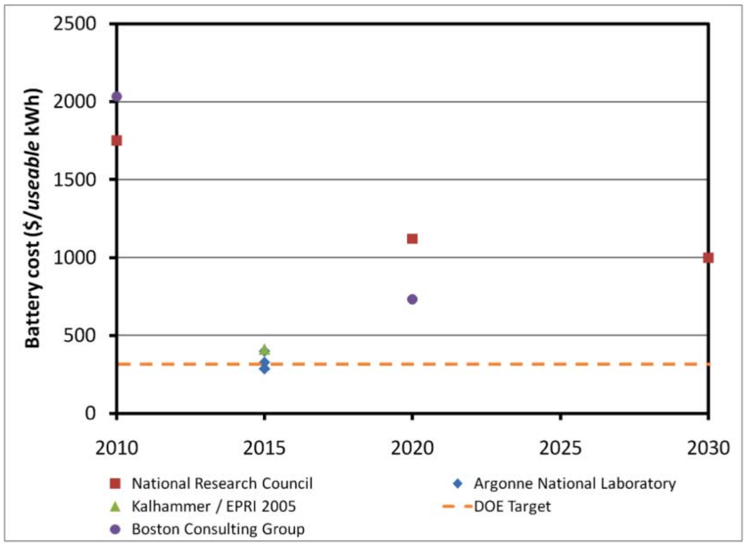

Figure 18
Battery cost assumptions of different studies

5.2 Energy Economy Ratio

A number of states and potentially the federal government are considering adopting policies similar to California's Low Carbon Fuel Standard (LCFS), which requires the lifecycle greenhouse gas emissions of fuels to decrease significantly over time. Since hydrocarbon fuels emit a given amount of greenhouse gasses when they are combusted this implies that either upstream emissions of fuels must be negative, as can be the case with efficiently produced biofuels, or that hydrocarbon fuels must be replaced with fuels with low or zero direct greenhouse gas emissions and low upstream emissions, like hydrogen or electricity. The LCFS includes a credit trading system that allows a wide array of fuels to be used as replacements for gasoline and diesel; however, due to the substantial difference in how fuels like gasoline and electricity are created and used it is difficult to trade these fuels on an equitable basis. In the LCFS, this equalization is done by rating the emissions of all fuels in terms of grams of CO_2 equivalent per megajoule, then adjusting these ratings by an Energy Economy Ratio (EER) to account for the differences in efficiency of fuel use. The EER accounts for the fact that fuels can be used to propel a vehicle more efficiently than others by comparing the efficiency of fuel use with the efficiency of gasoline use. For example, electricity has an EER of 4.0 in the standard, so a MJ of electricity is expected to propel vehicle four times further than a MJ of gasoline would propel a conventional vehicle.

It should be noted that in the LCFS it is assumed that the efficiency improvement of 30% required to meet AB 1493 (the 'Pavley' bill) will be met through gasoline engine and transmission efficiency improvements, which will not accrue to electric vehicles, so the official EER used for fuel equalization is discounted to 3.0. EPRI work indicates that the ratio of electricity efficiency to non-hybrid gasoline efficiency will be above 4, even with expected improvements in engine and transmission efficiency, as shown in Figure 19.

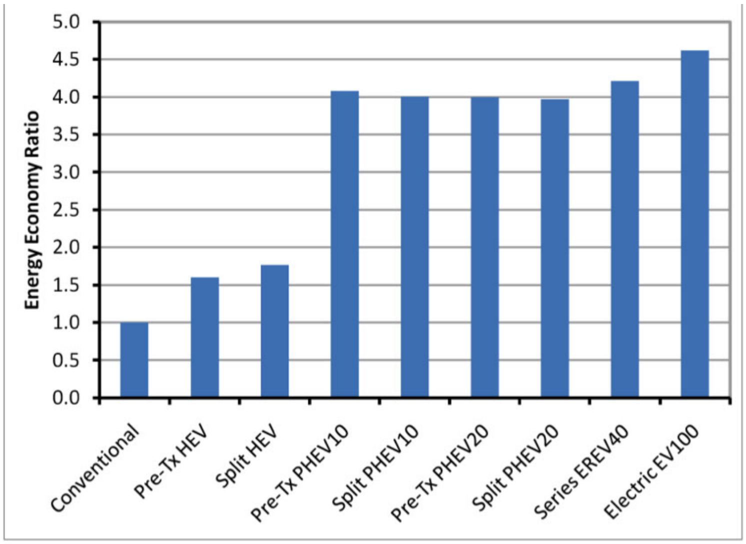

Figure 19
Modeled Energy Economy Ratios for Equivalent Midsize Vehicles

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Acknowledgements

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Plug-in Electric Vehicle Infrastructure: A Foundation for Electrified Transportation

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Abstract

Plug-in electric vehicles (PEVs)—which include all-electric vehicles and plug-in hybrid electric vehicles—provide a new opportunity for reducing oil consumption by drawing power from the electric grid. To maximize the benefits of PEVs, the emerging PEV infrastructure—from battery manufacturing to communication and control between the vehicle and the grid—must provide access to clean electricity, satisfy stakeholder expectations, and ensure safety. Currently, codes and standards organizations are collaborating on a PEV infrastructure plan. Establishing a PEV infrastructure framework will create new opportunities for business and job development initiating the move toward electrified transportation. This paper summarizes the components of the PEV infrastructure, challenges and opportunities related to the design and deployment of the infrastructure, and the potential benefits.

Introduction

Over the last 100 years, oil has become the dominant transportation energy source. The technical performance, cost, and convenience of oil have yet to be challenged by alternative power sources. In the coming years, oil demand is expected to exceed supply, causing price volatility and supply disruptions. Burning oil also results in emission of greenhouse gases that contribute to climate change.

One way that nations could rapidly address the concerns caused by reliance on oil is to electrify the transportation system and expand the amount of electricity generated from renewable sources. The challenges to making the necessary technology and market transitions are significant but not insurmountable if complete implementation plans are created to account for the needs of various stakeholders. The U.S. Presidential Administration's goal is to invest in advanced technology supporting introduction of 0.5 million plug-in electric vehicles (PEVs) by 2015.

Research on plug-in hybrid electric vehicles (PHEVs) by the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE) in the late 1990s began as a result of electric vehicle (EV) introduction challenges (1). EV market growth was hampered by many factors, including battery performance and cost, long battery-recharge times, low oil prices, and consumer expectations. "Range anxiety," the fear of being stranded in an EV because of insufficient battery performance and accessible charging infrastructure, kept consumers away from EVs (2).

PHEV technology builds upon hybrid electric vehicle (HEV) technology experience. A PHEV's battery capacity is 5–10 times larger than an HEV's but less than 1/4–1/3 that of a typical EV (3). This reduces the cost of PHEVs compared with EVs while providing EV operation for short-range driving and HEV operation for long-range driving. Thus, PHEVs offer fuel savings, flexibility, and extended driving range to consumers.

Because of the relatively small PHEV battery, initial expectations were that PHEVs would be charged at home from typical 120V outlets. However, since starting initial investigations of PHEV technology, the PHEV infrastructure scenarios have expanded significantly.

In parallel with PHEV development, states have moved toward rapid renewable energy expansion. Twenty-four states have adopted mandatory renewable energy standards, while five have adopted voluntary standards (4). The variability of renewable energy generation creates integration challenges (5, 6). PEVs represent a new, flexible electricity load, which could enable expanded renewable energy generation.

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Infrastructure to enable safe, efficient PEV charging and charge management has evolved rapidly in recent years. This paper summarizes the components of the PEV infrastructure as well as challenges and opportunities.

Discussion

It may seem simple to "just plug in" PEVs. However, for the PEV market to expand, a broad infrastructure plan is being developed to deliver consumer value and satisfaction. Effective infrastructure enables greater use of the battery technology, as shown in (7), where recharging throughout the day provided approximately 10% greater fuel savings using 50% less battery capacity. Fully using these resources depends on the following PEV infrastructure components, which are discussed in the subsequent sections:

- Energy Storage
- Charger – On-board/Off-board
- Cords and Connectors
- Electric Vehicle Supply Equipment
- Advanced Meters
- Home Area Networks
- Parking Lots and Neighborhoods
- Buildings/Multi-unit Dwellings
- Smart Grid
- Aggregation Algorithms
- Distributed Generation/Storage
- Renewable Generation
- Communications Architecture
- Information Technology

Energy Storage

With energy storage, grid electricity is stored on-board the vehicle. Energy storage combined with lightweight vehicle design and efficient motors, creates a competitive alternative to conventional vehicles. Lithium-ion battery technology is the likely energy-storage candidate for near-term vehicles.

The DOE Energy Storage program collaborates with industry to address life, cost, and safety challenges of energy storage (8). Energy storage life is affected by cycling routines and ambient storage conditions. Cost is affected by materials and manufacturing methods and volumes. Safety is affected by design, chemistry, and manufacturing methods.

Energy storage is an enabler of electrified transportation and international competition for energy-storage market share will emerge. The best use of limited supply of batteries must be investigated. Dedicating a large battery for a vehicle used less than one hour per day for personal travel may limit potential benefits. Large batteries could provide additional value, e.g., by providing grid services in or out of a vehicle. There is opportunity in analyzing the battery capabilities, potential value, and ownership scenarios.

Charger – On-board/Off-board

The power electronics for charging the energy storage system could be on-board or off-board the vehicle. Improving the efficiency and cost of this component may be critical to the success of electrified transportation. Weight of on-board units is also important. On-board units take AC power from the grid and rectify it to DC power to charge the DC battery pack. Off-board units make this same conversion and deliver DC power to the vehicle. Communication between the battery management system and the charger must occur to ensure energy is delivered safely. Power-quality standards for chargers are being developed with the goal of minimizing detrimental impacts to grid operation.

Vehicle charging infrastructure also offers the opportunity to reverse power flow from the vehicle battery to the grid. The value of this scenario must be balanced with its inefficiency and battery-life impacts.

Chargers and associated cords are categorized by voltage and power levels: Level I is 120V AC up to 20A (2.4kW), Level II is 240V AC up to 80A (19.2kW), and Level III (which is yet to be defined fully) will likely be 240V AC and greater at power levels of 20–250kW (9). It is expected that similar definitions will be created to categorize charging with DC power delivery. The value of each charge power level is tied directly to the size of the on-board battery pack and the time available for recharging.

Cords and Connectors

In the previous generation of EVs, cords and connectors became a point of debate and made introduction challenging. Today, SAE has led efforts to standardize a connector for conductive charging in the United States. The SAE J1772 standard defines a five-pin configuration that will be used for Level I and Level II charging (9). A Level III connector and the use of the current connector for DC power flow are under development. Tripping hazards due to cords in garage areas and public places may be a safety and adoption hurdle.

Electric Vehicle Supply Equipment

Electric vehicle supply equipment (EVSE) improves the safety of vehicle charging in accordance with the National Electric Code (NEC). The EVSE enables power flow between the electricity distribution system and the PEV only when a cord and connector are completely connected. For Level II charging, the cord is permanently attached to the EVSE and is de-energized when not connected to the vehicle inlet. The EVSE and charger may be a single component if the charger is located off-board the vehicle. In some regions, the EVSE will be attached to or include a sub-meter for measuring electricity delivered to the vehicle separate from electricity delivered to the rest of the premise. This feature supports low-carbon fuel standard accounting.

The installation of an EVSE in a building may present a significant hurdle to adoption because it involves multiple parties, including utilities, building inspectors, electricians, and vendors (12). The time from purchase to functioning installation might be as much as 30 days in some regions providing a less than ideal experience for consumers. Related codes and standards efforts are discussed below.

Advanced Meters

Investment by utilities and governments in smart-grid technology supports the improvement of utility operations. Advanced meters are likely to be the primary access point for utilities to gather information on consumer use and transmit information to consumers to alter their behavior. Advanced meters are not required to enable vehicle charging or charge management. However, future PEVs may be the most significant configurable load accessed by advanced meters.

Home Area Networks

Home area networks enable consumers to collect information on and manage the operation of their homes. The PEV, EVSE, sub-meter, and the advanced meter could be integrated into the home area network along with appliances, lighting, and heating and cooling systems. The home area network is likely to be a primary point of information access for consumers. Adoption rates are uncertain.

Parking Lots and Neighborhoods

It is expected that most PEV charging will take place in or near a primary residence. Charging in workplace parking lots is likely to provide the next greatest opportunity for oil displacement (10). Several studies compare the cost of infrastructure (11, 12). A critical challenge related to charging outside the home is managing multi-party use of infrastructure providing greatest cost-benefit ratio to the infrastructure owner/operator. Infrastructure planning methods along with measurement and billing functions need investigation. Algorithms for managing shared resources in neighborhoods and parking lots may be needed as markets develop. Previously, analyses showed the ability of generation systems to accommodate large populations of vehicles with at least some ability to shape the energy demands (15-18). Current analyses focus on the impacts on neighborhood distribution systems (19-24). Critical issues include overheating of transformers due to increased loads and coincidence of loads and imbalances in the three-phase system. As has been the case with HEVs, select neighborhoods are likely to see much higher than average PEV densities and potential overloading. Multiple vehicles on a single phase of a three-phase distribution system could cause phase-to-phase imbalances resulting in induced magnetic fields that may affect the surroundings. Utility planning and operational data analysis could be used to prevent problems.

Buildings/Multi-unit Dwellings

The strength of the relationship between PEVs and buildings are situational. For residential areas, home area networks and advanced meters should enable significant integration. In commercial and public areas, Leadership in Energy and Environmental Design (LEED) building certifications assign value to the use of alternative fuel vehicles. PEV loads may need to be managed to avoid increases in peak demand charges. Innovative solutions may exist to integrate vehicle services (charge and discharge), building load management, and renewable energy generation to optimize total cost savings and value delivered. A significant challenge will be planning and coordinating access to charging resources. Waiting for access will be unacceptable for PEV customers and non-PEV customers are likely to be irritated by unoccupied but reserved parking locations. Installation, access, billing, and management of vehicle charging in dense residential/commercial areas are challenges to be resolved.

Smart Grid

Smart grid technologies open a new door for system optimization. The smart grid allows utilities to better understand their needs and resources and optimize system use. Various levels of implementation likely will exist, from data monitoring and remote controls throughout the entire network to basic automation of meter reading. Although smart grid implementations may vary regionally, this technology may enable vehicles to roam from one utility network to another if basic interoperability standards are adopted across broad regions. The smart grid may also enable integrating greater levels of renewable energy resources by combining generation data with load-management potentials and resource planning.

Aggregation Algorithms

Aggregation services collect a diverse or common set of vehicle loads to create a more desirable load. This is a new and evolving area. Research by the National Renewable Energy Laboratory, Xcel Energy, and Gridpoint (formerly V2Green) demonstrated initial aggregation algorithms in field tests (14). Denholm and Sioshansi analyzed vehicle fleets in the Electric Reliability Council of Texas (ERCOT) region under utility management in aggregate, highlighting the fuel savings and emissions benefits (25). Others, including Enernoc and the MAGIC Consortium, have begun to explore aggregation of loads and sources to provide grid services. Aggregation algorithms will be refined as operational data is collected. A recent report by ISO/RTO Council highlights aggregation of vehicle loads as a necessary step to enter nearly all grid service markets, which would extend the value of the vehicles beyond just oil displacement (26). Proliferation of aggregation may be highly dependent on consumer monetary or perceived value. Aggregation of diverse loads provides the flexibility necessary to deliver perceived value of dedicated "green" energy supplies to vehicles.

Distributed Generation/Storage

Distributed storage systems that dynamically aggregate and filter a collection of loads—such that the collected load is smooth, consistent, and repeatable—aid in the efficient and cost-effective delivery of electricity. Electrochemical energy-storage technologies, such as PEV batteries, have not yet been cost effective for grid applications. Market expansion could benefit vehicle and grid operations if common energy-storage attributes are identified so that production volumes could be increased. The work of American Electric Power (AEP) on community energy storage and Southern California Edison (SCE) on the “garage of the future” are consistent with developing complementary markets for energy storage in mobile and stationary applications (27, 28).

Renewable Generation

The variability of renewable electricity generation is managed in multiple ways, including geographic diversity, computer forecasting, operational controls, and planned flexible resources. Renewable generation variability has integration costs (5, 6, 29). Experience suggests that wind generation will be greater in the evenings and at high penetrations it conflicts with minimum output levels of fossil power plants. A significant amount of energy for PEVs will be needed at night, which helps address wind energy integration challenges. The response time of batteries and chargers to load-management commands should be much less than one minute, which is faster than nearly all flexible resources in the grid today. State Renewable Portfolio Standards set goals for renewable integration, and the parallels between these standards and vehicle introductions is an area meriting further study.

Communications Architecture

Communications architecture has been a strong component of economic growth in the US since the introduction of microprocessors in the 70’s (30). It is the physical backbone that enables business to function today. U.S. communications architecture provides the opportunity for PEVs to be an active participant in the future grid. SAE standards groups are developing the expectations and implementation methods to enable PEV communication. The information to be passed is critical while the physical means by which it is passed is less critical as long as interoperability is ensured. The need for security features will become more important as utilities base operational decisions on information transferred over communications networks.

Information Technology

Information technology is needed to manage the movement of data between parties and to transform these data into knowledge and decisions. The computational power needed to manage the Smart Grid to its fullest extent has yet to be determined. Creating a multilayered operational network using embedded systems may provide a robust, efficient, flexible, responsive system relative to the centrally managed approach used today.

Future Scenarios

The infrastructure components discussed above summarize the status and potential of near-term PEV implementation. These components could be integrated with additional scenarios.

Lightweighting of PEV systems could optimize the use of a limited supply of energy-storage technology (30). Intelligent transportation networks with roadway-to-vehicle and vehicle-to-vehicle communication may reduce congestion and increase safety. Plentiful and simple vehicle-charging infrastructure supports the evolution of car sharing and enables smooth transitions between multi-modal systems. Other scenarios include roadway power delivery (32) and wireless power delivery (33).

System Integration and Interoperability

Interoperability of PEV infrastructure components is critical for widespread deployment of PEVs thus enabling new businesses and jobs. Multiple standards entities are focusing on developing codes and standards supporting PEVs and grid integration. Blake et. al. summarize codes and standards associated with alternative fuel vehicles (34), and (12, 26) summarize standards related to grid integration and future service options. Select standards activities related to infrastructure are discussed below.

In the United States, SAE is creating standards defining the connection points and interoperability of PEVs with the rest of the infrastructure. SAE J1772 defines the standard connector to be used between the PEV and infrastructure for conductive power delivery. SAE J2836 defines usage scenarios of PEVs with utility programs and J2847 defines the communication message content and structure between PEVs and the grid. Together these create a basis for interoperability. SAE J2894 is being developed to define power-quality requirements for chargers.

Standards and testing organizations—including the National Institute of Standards and Technology, Underwriters Laboratories, and National Fire Protection Agency—are collaborating to define grid safety and integration methods. IEEE has developed IEEE 1547, and is working on P2030, to define interoperability for distributed generation and loads along with communication standards between these components and the Smart Grid. EPRI's Infrastructure Working Council facilitates coordination among industry, government, and standard groups.

In Europe, the International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) bodies lead the development of standards for PEVs. In Japan, the Japan Automobile Research Institute (JARI) is developing guidelines and standards for integration of vehicles. The development of worldwide standards for connectors, operational scenarios, and information transfer would be beneficial. Coordination with international entities is a high priority for DOE. The most significant challenge related to codes and standards is the coordination of activities across multiple standards bodies and industries.

Roaming

"Roaming" of PEVs is important for building consumer satisfaction and confidence. With more than 3,000 U.S. utilities, consumers likely will interface with multiple utilities when charging PEVs outside their homes. The costs and options for charging at home versus roaming may vary significantly. There are parallels with the early introduction of mobile phones. When roaming, consumers encountered high costs and service frustrations until the network and contractual relationships evolved. Although it may be less significant for PHEVs, which have an ICE for extended driving and will get charged most often at home, market introduction of PEVs in general could be hampered by roaming problems.

Infrastructure Challenges and Opportunities

Many of the challenges to PEV infrastructure are presented above. The primary challenge is component interoperability within the system, which standards bodies are addressing. Coordination with international entities is another issue; successful coordination would lower the cost of market expansion by providing manufacturers with greater volumes of consistent products.

Developing a PEV infrastructure also presents opportunities. Energy storage technology is the fundamental element needed for PEV market evolution. While high battery costs limit market penetration, identifying multi-value stream pathways for PEV energy storage is important. The parallel growth of renewable energy provides new integration opportunities for flexible resources. PEVs may be a suitable flexible resource because of their fast response and broad window of opportunity for charging. Charging patterns will depend on consumer behavior, which can be assessed and influenced via the smart grid and predictive-behavior tools.

Finally, there is opportunity to determine how CO_2- and oil-displacement credits will be allocated to PEVs; this topic is not covered adequately in the current literature. Sub-metering efforts in California are establishing the data-collection methods for verifying electrical energy delivery and consumption by vehicles. An NRDC/EPRI (35) report highlights the relative CO_2 impacts of the source of electricity used for PEVs. Although the energy delivered to a PEV may not have been generated directly by a renewable source, if its flexibility in operation enables expansion of renewable sources at a lower cost of integration, then there is a substantial CO_2 impact.

Conclusion

The confluence of battery technology developments, oil prices and price volatility, renewable generation and integration technology, and environmental concerns is uniting government and industry behind a transition to a transportation system that does not depend on oil. PEV infrastructure will transform how energy is delivered to vehicles. The infrastructure to support the introduction of PEVs is much more complex than an extension cord and outlet as previously assumed. PEVs will connect to the new transportation system through many, yet-to-be-developed infrastructure components forming a foundation for an electrified transportation system. Interoperability of these components is a core role of DOE, national laboratories, industry, and standards organizations. International collaboration should accelerate market expansion. The challenge to develop a robust, flexible, renewable, low-cost system for vehicle energy delivery while providing confidence, comfort, and value to the consumer will form the core of research programs over the coming years.

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Electric Vehicle Policy[1]

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A Vision of the Future

If the United States (and the rest of the world) is gong to significantly reduce greenhouse gas (GHG) emissions and petroleum use, the transportation sector will need to be transformed. With sustainability as the goal, the future will almost certainly move away from the US car-centric model—where almost all surface travel is by 1.5-3 ton vehicles, usually with a single occupant.

It is widely accepted that electric-drive vehicles will gradually supplant internal combustion engine vehicles, especially for passenger travel.[3] These electric-drive vehicles would be powered in part by electricity generated by power plants with near-zero carbon emissions, along with hydrogen made from a mix of renewables and natural gas and perhaps even from coal with most of the carbon sequestered. The remaining electric-drive vehicles might be very efficient hybrid-electric vehicles powered in part by biofuels made grasses, trees, algae, crop and forestry residues, and municipal waste. Choices will expand. Convenience and sustainability will become primary considerations, and carbon emissions associated with travel would drop dramatically.

For this future world to take root, an entirely new set of incentives, regulations, and policies must be put in place. These incentives are needed to motivate consumers, governments at all levels, and businesses to respond to goals of reduced carbon and oil use.

New and enhanced technology is needed, but the greatest challenges are changes in the behavior of individuals and organizations. Greater use of real-time information and enhanced wireless communications will facilitate a revolution in mobility services, including smart car sharing, dynamic ridesharing, and demand responsive jitneys. The proliferation of these mobility services would lead to more specialization of vehicles, including much greater use of neighborhood electric vehicles, or ultra-small vehicles.[4] Even more crucial are changes in behavior to embrace the new fuels and vehicle technologies that are and will be forthcoming. New incentives will be needed to motivate socially rational behavior by giving tomorrow's consumers and companies much clearer signals about the impacts of their choices and investments. Market signals and incentives would also need to be applied to land developers and local governments. The end result is that cities and individuals would be motivated and empowered to find ways to reduce energy use and carbon emissions.

Three Sets of Changes

Three sets of changes are needed to realize this vision of the future: vehicles must become far more energy efficient, the carbon content of fuels must be greatly reduced, and consumers and travelers must behave in a more eco-friendly manner. All three sets of changes are key to the future of electric-drive vehicles.

The automotive transformation is already beginning. Automakers are shifting toward electric-drive vehicles that use electric motors for propulsion and to control steering, braking, and acceleration. They are moving from mechanical and hydraulic controls to electronic and computer controls. The first generation of electric-drive vehicles, gasoline-electric hybrids, are still fueled by petroleum fuels, with the fuel converted into electricity onboard the vehicle. But several major automakers are about to unveil battery electric and plug-in hybrid vehicles that will operate mostly or totally on electricity—motivated by increasingly stringent fuel economy and GHG standards for vehicles and by California's zero-emission vehicle program. And automakers continue to invest in hydrogen-powered fuel cell electric vehicles that could reach mass commercialization in the next decade and beyond. This evolution toward efficient, electric-drive vehicles is clear and definite—it's more a question of how fast it will occur.

With transportation fuels, the path to the future is less certain and likely to be considerably slower. While biofuels are already well established in two regions, America's farm belt and Brazil, these first generation ethanol biofuels use large amounts of land and water and have relatively high carbon footprints. Biofuels of the future will more likely come from waste materials—crop residues, forestry wastes, and urban trash—plus grasses and trees in areas where food crops don't grow well, and possibly algae. Advanced biofuels will mostly likely be diverted to jet engines and long-haul diesel trucks, where energy density is highly valued. Passenger and urban freight vehicles will more likely depend upon electricity and hydrogen, used in battery, plug-in hybrid, and fuel cell vehicles. But the transition to electricity and hydrogen will require transformations of the very large companies that dominate the automotive and oil industries, and thus will proceed slowly.

The third arena, eco-friendly travel behavior, is the most problematic. Cars are firmly entrenched in our culture and modern way of life. Reducing inefficient car dependent vehicle travel requires reforming monopolistic transit agencies, anachronistic land use controls, distorted taxing policies, and the mindsets of millions of drivers who've been conditioned to reflexively get into the car every morning. It's much more challenging than transforming a small number of energy and car companies. But even in California, the birthplace of car-centric living, the realization is starting to settle in that mobility must be more sustainable. Spurred by escalating gas prices and accelerating evidence of climate change, consumers are already beginning to recognize that the transformation of the car-centric monoculture is long overdue. The shift away from large passenger cars and trucks as the overwhelming mode of choice is critical to the future of battery electric vehicles (BEVs). Because of the cost and bulk of batteries, BEVs will thrive mostly in local use where trips are short and speed and performance less important. BEVs thrive in these applications, as complements to other vehicles and mobility services.

Strategy for Getting There

To realize this future vision of a lower-carbon, less oil-driven future, we need a strategy for getting there—a pragmatic, action-oriented approach inspired by innovation, fueled by entrepreneurialism, and sensitive to political and economic realities. This approach must be rooted in and responsive to the realities of today, but with an eye to the future.

The recommendations that follow are guided by two overarching principles. First, enact policies to align consumer and industry private interests with the public good. And second, develop and advance a broad portfolio of efficient, low-carbon technologies to transform transportation.

Policymakers must overcome the temptation to prescribe and mandate any one particular solution. While there's a role for prescriptions and mandates in addressing societal problems, there's an even more compelling need for durable policy frameworks that permanently shift consumer and industry behavior (and also the behavior of governments themselves).

Similarly, they must resist the temptation to pick winners. There's an unfortunate tendency for technological experts and politicians alike to embrace "silver bullets" and pick winners. Innovation and technological changes are too dynamic and too difficult to predict. Not even highly savvy experts, much less seasoned politicians, can accurately determine which exact technologies will prevail. It's self-defeating to pick winners, in part because technologies once selected and blessed often take on a life of their own, with entrenched interests championing them. The result is a technological determinism that loses sight of its original goal. The prime example is America's hugely subsidized corn ethanol industry. It provides few societal benefits—and has many drawbacks—yet its now-powerful political and economic constituency resists all efforts to phase it out.

The simplest way to avoid the temptation to pick winners and prescribe specific changes is to impose performance standards. This advice is simple—yet routinely ignored. The use of performance standards, codified into durable policy frameworks, will invigorate competition among different fuels, vehicles, and mobility services, promote technological breakthroughs, and spur marketing of new technologies. It will empower manufacturers and consumers to take more responsibility for reducing energy use and carbon emissions.

In summary, a new approach is needed that engenders individual and corporate accountability, promotes innovation, balances private and public interests, and endures over the long run. The tools of this transformation are incentives and regulations, and research, development, and demonstration (RD&D).

Table 1: Strategy for transforming vehicles, fuels, and behavior

TOOLS	TRANSFORMATIONS		
	Energy-efficient vehicles	***Low-carbon fuels***	***Green consumer and government behavior***
Incentives and regulations	Ratchet up fuel economy and GHG standards for cars and light trucks over time Develop fuel economy and GHG standards for large trucks Increase California's zero-emission vehicle requirements	Impose low-carbon fuel standards for fuel providers Create incentives to develop a low-carbon fuel infrastructure	Reward low-carbon consumerism (fuels, vehicles, and travel) Restructure taxes, fees, and other incentives to reduce vehicle usage Establish carbon budgets for individuals, households, and local governments to reward low-carbon behavior and discourage sprawl Create incentives to advance new mobility options
Research, development, and demonstration	Expand basic research and demonstration of advanced vehicle technologies	Expand R&D for low-carbon fuels Facilitate global development of low-carbon technologies, standards, and treaties	Research, develop, and test new mobility services Develop and test strategies to motivate low-carbon behavior

Transforming Vehicles

The most effective and least costly way to reduce transportation oil use and greenhouse gas emissions is to improve the energy efficiency of vehicles.[5] Yet, for twenty-five years, from the early 1980s to 2008, the fuel economy of new cars and light trucks in the U.S. remained stagnant. Vehicle technology improved dramatically, but the energy-efficiency improvements were diverted to serving private desires for bigger and more powerful cars—especially in the United States. The challenge is to capture more of the benefit of technology improvements to serve the public interest, even if that means scaling back vehicle size, weight, and especially power and performance. Even more gains are possible with an accelerated transition to electric-drive vehicles. Following are recommendations to reduce fuel consumption and carbon emissions.

Ratchet up fuel economy and greenhouse gas standards over time

The most powerful and effective action available to government is to ratchet up vehicle performance standards. All countries with advanced economies, except Australia, even China, have adopted such standards. The US Energy Independence and Security Act of 2007 boosted fuel economy standards by 40 percent, requiring cars and light trucks to achieve 35 mpg by 2020. In April 2009, President Obama accelerated this schedule, declaring that the 40 percent improvement must be by 2016. Obama's announcement was precipitated by California and fifteen other states that had already adopted laws and rules requiring the roughly 40% improvement by 2016.

Vehicle performance standards are the most effective policy instrument for reducing oil use and greenhouse gas emissions when markets fall short. American automakers have complained in the past that these standards force them to sell cars that consumers don't want. They've argued (but never lobbied) for high fuel taxes as a better way to improve fuel economy. But even Europe and Japan, with much higher fuel taxes than the United States, find that stringent vehicle standards are needed to improve fuel economy and reduce greenhouse gases. The stark reality is that market forces (short of draconian taxes) have proven inadequate by themselves to motivate such improvements.[6] The growing wealth of new-car buyers exacerbates consumer undervaluation of fuel economy and climate change in the vehicle purchase decision.

Develop dynamic fuel economy and greenhouse gas standards for heavy trucks
The greater energy and climate change challenge is with heavy trucks. Their fuel economy has never been regulated, for two reasons. First, truck makers argue that fuel costs are such a big part of doing business that the normal workings of the market are sufficient motivation to improve fuel efficiency. And second, truck designs vary so much and trucks are used in so many different ways that regulation has been impossibly difficult. But truck and engine builders now confirm that greatly improved truck efficiency is possible.[7] And in 2006, Japan's regulators made a breakthrough. They began the process of regulating trucks using mathematical models to simulate fuel use for different applications and mixes of engines and vehicle types.[8] The Japanese example blazes a new trail that makes possible heavy-duty truck regulation.

Substantial reductions are also possible from shifting the movement of goods to more efficient means such as rail. In some cases reductions could be large. But because the complexities of freight systems aren't well understood and unforeseen consequences for the economy can be large, policymakers are reluctant to intervene—probably with good reason. The challenge of transforming freight systems is even more daunting than transforming passenger travel and urban land use.

Increase California's zero-emission vehicle requirements and/or provide special credits for advanced vehicles
In general, performance standards are preferable to prescriptions and mandates. But something more than performance standards is needed to kick-start plug-in hybrid, battery electric, and fuel cell vehicles—especially because the nature of big organizations is to resist disruptive innovations. California's zero-emission vehicle program has played this role since its passage in 1990. The mandate has led a tortured life, but has been effective at focusing automaker attention and resources on advanced technology. It appears to be the best tool for accelerating the early commercialization of electric-drive vehicles.

The current requirement in California, adopted in early 2008, is modest: 7,500 fuel cell vehicles or 12,500 battery electric vehicles between 2012 and 2014 (or some combination), plus 58,000 plug-in hybrids. That requirement gives companies time to lock in final designs and test the market. California's Air Resources Board plans to greatly increase the requirements for 2015 and beyond. This California program, already adopted by a dozen or so other states, is a model for the United States and other nations as well.

Another related mechanism for accelerating the commercialization of advanced electric-drive vehicles is to provide additional credit to manufacturers through existing performance standards. For instance, a battery electric vehicle might be rated as zero grams per mile for purposes of complying with GHG vehicle performance standards. And one might go even further, offering multiple credits to those vehicles. A battery EV sold by Ford might count as three vehicles and be rated as zero. In this case, no subsidies are given to an automaker, and Ford would have flexibility in how many advanced vehicles it sold. The assigned GHG value and the determination of number of vehicle credits offered to battery EVs, PHEVs, and FCEVs can be adjusted over time.

Expand research and development of advanced vehicle technologies

A massive investment in research is needed to support and accelerate the development of energy-efficient, low-carbon fuels and vehicles. The majority of this funding must come from industry. Both the automotive and energy industries are populated by huge companies with strong research capabilities and financial resources that dwarf those of governments. Automotive companies are already devoting huge resources to vehicle propulsion, a core technology for vehicles. Government R&D funding is also needed, but it should be a small part of the total.

The primary role of government is to support basic research at universities and national laboratories. Industry is neither well qualified nor inclined to conduct such research. This basic scientific research is the underpinning of technology advances by industry—for all new technologies but especially those with large environmental and public benefits. The U.S. government has devoted about $200 million per year to automotive research for many years (through President Clinton's Partnership for a New Generation of Vehicles and President Bush's follow-on FutureCAR). Unfortunately, relatively little has gone to basic science and not enough has gone to universities. The one area where more funding is needed is in building a stronger science foundation for batteries, fuel cells, and hydrogen storage. Much of this is basic material science research.

A second government function relating to automotive technology is to support the demonstration of advanced vehicles. This need not be costly—and it doesn't mean government has to support the vehicles themselves. Most of the vehicle funding can come from industry. But companies will invest only if they're assured that government leaders will work with them to facilitate the acceptance of the technology. Industry needs local governments to modify codes and standards to support (not restrict) the new technologies. And it needs state governments to support and fund training programs for technicians at junior colleges, and to work with energy companies to provide energy stations to fuel vehicles powered by hydrogen and electricity.

Transforming Fuels

Dramatic changes are needed in the energy sector. Given the flawed marketplace and absence of guiding policy, today's oil industry is maximizing private gains, as explained in Chapter 5 of Sperling and Gordon, *Two Billion Cars.* But that behavior isn't in the public interest. Oil markets are unresponsive to prices, largely ignore greenhouse gases, and invite geopolitical conflict. Massive investments are being directed toward high-carbon unconventional petroleum.

New policies are needed that spur energy companies to invest in low-carbon fuels and necessary infrastructure. Large oil companies need to be encouraged to transition into broader energy companies that are less dependent on fossil energy. Many politicians and companies across the United States and other affluent nations are embracing the need for a more coherent approach to energy. But, alas, the public debate is focusing on corn ethanol and policies unlikely to have much effect on transport fuels, including carbon taxes and cap-and-trade programs. And where policies have been adopted—the biofuels (and renewable fuels) directive in Europe and the renewable fuel standard in the United States—they're deeply flawed. Following is a policy suggestion of how to transform fuels, acknowledging political and economic realities but with an eye toward energy and climate sustainability.

Impose low-carbon fuel standards

A low-carbon fuel standard would require oil companies and other fuel providers to reduce carbon and other greenhouse gas emissions associated with transportation fuels.[9] As first enacted in California, it would impose a carbon intensity standard on all fuels provided to vehicles, including electricity. Oil suppliers would decide how to meet the standard, whether by blending low-carbon biofuels into conventional gasoline, selling low-carbon fuels such as hydrogen, or buying credits from low-carbon electricity generators.

The idea of imposing a low-carbon fuel standard is highly attractive because this approach provides a durable framework, doesn't pick winners, encourages innovation, and sends a direct, unambiguous, fuels-neutral signal to fuel providers that alternatives are welcome. It's a hybrid of regulatory and market approaches, which makes it more politically palatable (and economically efficient) than a purely regulatory approach. Behind vehicle standards, it's arguably the second most compelling policy instrument for reducing greenhouse gas emissions from the transport sector. Implementation of such a standard is central to solving the greenhouse gas problems attributed to transport fuels.

California adopted a low-carbon fuel standard in April 2009, which took effect in 2010. Serious proposals for such a standard were under discussion in early 2008 in Japan, two Canadian provinces, and many U. S. states. The EU is also moving in this direction, after earlier adopting a biofuels directive that called for 5.75 percent replacement of gasoline and diesel fuel by biofuels by 2010.

Create incentives to develop low-carbon fuel infrastructure

America's renewable fuel standard and Europe's biofuels directive target liquid fuels. Oil companies will undoubtedly take principal responsibility for distributing and marketing those fuels (though they might not produce them) and thus will assume responsibility for building an appropriate fuel distribution infrastructure. But what about the more promising low-carbon fuels: electricity and hydrogen? Because the barriers to these nonliquid fuels are far greater than the barriers to biofuels, greater attention needs to be given to supporting the early fueling infrastructure for electricity and hydrogen. Incentives are needed to overcome uncertainty about oil prices, as well as oil industry ambivalence and even hostility.

Several options are possible. Government could provide funding derived from carbon-indexed fuel taxes, where a higher tax would be imposed on fuels higher in carbon (on a life-cycle basis). Carbon-indexed fuel taxes would have a relatively modest effect at first in transforming fuels or reducing fuel use, but they could be a source of revenue initially to support new fuel infrastructure. With future vehicles likely outfitted with transponder devices that could be coded with the vehicles' certified greenhouse gas attributes, it would be possible for vehicles to communicate with the fuel pump (or electricity charger) to determine the correct tax.

Incentives to develop low-carbon fuel infrastructure could also come from the auctioning of emission credits under a carbon cap-and-trade program.[10] While cap-and-trade programs will likely have little effect on fuel suppliers, they could be effective at generating substantial funds for use in subsidizing the timely deployment of electricity and hydrogen fueling stations.

Another approach to ensure development of early nonliquid-fuel stations is to require that petroleum fuel suppliers make electricity and hydrogen available at a certain percentage of their gasoline stations in coordination with expanding sales of electric, plug-in hybrid, and hydrogen fuel cell vehicles. California adopted a "clean fuels outlet" requirement in 1990 for methanol and compressed natural gas and is now considering applying it to electricity and hydrogen supply.

Still another approach is to give energy suppliers extra LCFS credits if they provide hydrogen and electricity charging and fueling stations.

Facilitate global development of low-carbon technologies, standards, and treaties

Transfer of innovative, low-carbon technologies, standards, and treaties between the developed and developing nations must be facilitated and encouraged. Such transfers will be of the utmost importance in inducing innovation and change. Studies show that programs and agreements aimed at knowledge sharing, research, development, and demonstration, when combined with aggressive domestic and international policies, could accelerate the global response to climate change.[11] Establishing consistent cross-national policy requirements, adopting coordinated agreements, and harmonizing energy and carbon markets are also useful strategies.

Most critical is the relationship with China and India, with their huge populations, growing economies, and huge reserves of coal. It's in the interest of the coal-rich United States to collaborate with these two countries to learn how to exploit coal more sustainably, share that technological know-how, give incentives for the adoption of best practices, and reward those who arrive at innovative solutions first.

Perhaps most important is collaboration and cooperation with China on BEVs. China is preparing to leapfrog ahead on electric vehicles. At an electric vehicle forum in Beijing in September 2009 organized by the U.S. Department of Energy to launch collaborations with the Chinese government and industry, U.S. officials were shocked by China's rapid progress. David Sandalow, assistant secretary of policy and international affairs for DOE and lead official for the Obama administration, was stunned to learn that China already had about 80 million electric bikes and scooters on the road and was building a massive EV industry. Wan Gang, China's minister of science and technology, in his introductory talk left no doubt as to the nation's intent. He proudly proclaimed that China was building the industrial foundation for EV manufacturing. China indeed is well on its way to establishing itself as the center of the global EV industry. Many of its hundreds of electric bike and battery companies are now moving upscale. Manufacturers are starting to build small three- and four-wheeled electric cars and advanced lithium-ion battery packs for them. One aspiring EV company, BYD, so impressed Warren Buffet, renowned for his investment acumen and one of the richest people in the world, that he invested $230 million for a 10-percent share.[12] With little intercity travel and short, congested commutes, the Chinese market is ripe for EVs.

Transforming Consumer and Local Government Behavior

Automakers can ultimately build efficient vehicles, and energy companies can supply low-carbon fuels. But unless consumers are willing to buy more efficient vehicles that use low-carbon fuels and to reduce vehicle travel, there's no hope of reducing oil use and greenhouse gases. Thus, the focus here is on consumer behavior—as well as local governments, who operate and manage and indirectly influence much of the transportation system, particularly transit services. They also regulate land use, which has a large effect on vehicle usage. Only with enhanced transport choices and smarter land use can individuals and cities reduce their carbon footprints.

Reward low-carbon consumerism

We begin with individuals and their purchase of vehicles. Without an incentive to alter their habits, consumers tend to maintain the status quo, even when aware of adverse impacts. High oil prices (assuming they continue) provide some incentive for low-carbon vehicle purchases, but even so consumers are likely to overlook or undervalue the environmental impacts and energy savings of new vehicles, fuels, or other products. Their behavior may be the result of market failures, ignorance, or just lack of engagement. Whatever the reason, financial incentives and disincentives rivet consumer attention on the impacts of their choices and influence their buying behavior.

Financial incentives and disincentives include rebates and surcharges.[13] These are important strategies to align consumer behavior with shifts in automaker offerings in response to stringent fuel economy and greenhouse gas standards, especially if fuel prices prove as volatile as they have in the past. The success of these financial policies is tied to three key factors. First, they must be sensitive to equity implications—they can't be seen as hurting disadvantaged people. Second, dollar amounts must be set high enough to have a meaningful effect on consumer, manufacturer, fuel supplier, and car dealer behavior, but not so high that they provoke strong political opposition. And third, they're most effective when linked with a specific regulatory goal such as fuel economy and greenhouse gas standards imposed on automakers and fuel suppliers.

A remarkably large number of incentives aimed at focusing consumer attention on new vehicle fuel economy and carbon emissions are now being enacted around the world—much more so than in the United States.[14] Such incentives range widely by country and often vary by a vehicle's carbon emissions, weight, engine size, or other related factor. In Denmark, for example, consumers who buy cars using less than 3.6 liters of gas per 100 kilometers (58.8 mpg) get a rebate on the country's high car tax (which can amount to up to 105 percent of the vehicle's value).[15] Ireland, on the other hand, imposes a variable tax, from 22.5 to 30 percent, based on a new vehicle's engine size. And the Netherlands adopted a so-called "gulp tax" in early 2008 that imposes a large tax on sales of gas guzzlers. Other countries, such as France, have recently adopted policies that bundle incentives and disincentives together. Cars emitting less than 130 grams of carbon dioxide per kilometer (g CO_2/km) receive a 5000 Euro (€) rebate, while those emitting more than 250 g CO_2/km pay a 2600 € fee, and those between 131 and 160 neither pay a fee nor receive a rebate.[16]

The idea behind such "feebate" policies[17] is simple: impose fees on consumers who purchase vehicles that guzzle gas and pollute, and award rebates to those who buy fuel-efficient, low-emitting vehicles. The impact of a feebate program depends on its structure. One study in California projected that combining the state's (pending) greenhouse gas vehicle standards with the feebate program almost adopted by the legislature in 2007 would have reduced greenhouse gases up to 25 percent beyond what the standards themselves would achieve.[18]

Consumer incentives are attractive not only because they shift consumer purchase decisions but also because they motivate manufacturers to accelerate the development and adoption of lower-carbon, fuel-efficient technologies.[19] Feebates give automakers and their technology suppliers the certainty of knowing that fuel economy will be highly valued into the future even as gasoline prices ebb and flow. This inspires more innovation and more commitment to getting energy-efficient technology into vehicles.

Local governments can also influence buying behavior by offering a variety of nonmonetary incentives to those driving low-carbon vehicles, such as free parking and use of high-occupancy vehicle lanes. In the 1990s, many cities in California installed charging stations for electric vehicles in parking areas and offered free parking to the vehicles. Los Angeles International Airport offers free parking for electric vehicles in two of its parking structures. A few states, including Virginia and California, allow electric and natural gas vehicles as well as a certain number of the most efficient hybrids to use carpool lanes with just a single occupant.

Restructure taxes, fees, and other incentives to reduce vehicle usage

Once people buy a car, they rarely consider using other modes of transport. One reason is that they perceive the marginal cost of driving to be very low, usually just the cost of gasoline, tolls, and parking in downtown areas. They ignore not only a raft of burdens they impose on others—air pollution, noise, climate change, energy insecurity, and increased traffic congestion—but also costs to themselves from the vehicle's wear and tear, insurance, depreciating value, and other ancillary expenses.

Part of the problem can be solved by restructuring the way fees and taxes are charged. Examples include fuel taxes indexed to carbon content, congestion fees, and more favorable tax treatment of new mobility options—such as reducing or waiving sales and registration taxes for vehicles used in carsharing, formalized carpool arrangements, and commercial paratransit service, and even waiving bridge and road tolls for these same vehicles. These incentives work together to promote less dependency on high-carbon cars with a single occupant and more on innovative mobility services.

The more fundamental problem of assuring that drivers make decisions based on the real cost of driving can be addressed by converting fixed (or intermittent) costs into variable costs. One such expense that could be converted is insurance. This policy, known as pay-as-you-drive (PAYD) insurance, ties insurance payments to how much a driver travels. The insurance cost could be paid at the pump, along with the fuel cost, or charged monthly based on odometer readings.

Many insurance companies support this concept, in part because it also solves the problem of uninsured drivers.[20]

Another innovative way to restructure vehicle expenses, championed by Professor Donald Shoup of UCLA, is to give commuters cash in lieu of free parking.[21] Many employers offer free parking to workers as a fringe benefit, but this is a subsidy for driving. Why not make the value of this benefit directly available to all employees? Some employees will choose to park for free but others will choose to accept a certificate that can be used for transit or cashed (if they bike, walk, or telecommute). The net effect is to reduce vehicle use. California mandated parking cash out, but many exemptions and too little publicity have prevented enforcement statewide, except in Santa Monica. According to the California Air Resources Board (the program's administrator), many California employers don't realize that they should be cashing out free parking for their workers. A study of eight firms that complied with California's cash-out requirement found that the number of people driving solo to work fell by 17 percent, carpooling increased by 64 percent, transit ridership increased by 50 percent, the number of people who walked or biked to work increased by 39 percent, and vehicle commute travel at the eight firms fell by 12 percent.[22]

In addition to giving travelers incentives to leave their cars at home, there are other ways to use information to reduce energy use and greenhouse gas emissions of vehicles—what Europeans are calling eco-driving. The theory is that more information will lead to better driving and car maintenance habits that reduce carbon emissions. Inflating tires to proper pressure, tuning engines more frequently, keeping air filters clean, aligning wheels, driving less aggressively, speeding less, minimizing air conditioning, and removing roof racks all help. Gentler driving, for instance, can reduce fuel consumption by up to 25 percent or more, according to studies in Europe, where eco-driving is more actively promoted.[23] A Belgian study compared aggressive and relaxed driving of four different cars and found that aggressive driving consumed as much as 60 percent more energy over an urban and rural driving cycle than a relaxed eco-driving style (though the savings are considerably less in most cases).[24] Drivers of some new high-end cars, as well as hybrids, have dashboard instruments that show them how much fuel they use on a second-by-second basis.

Establish carbon budgets and banks for individuals, households, and local governments

Consider that individuals and cities readily accept that they must live within a financial budget. Why not also within a carbon budget?[25] The appeal of carbon budgets is that they push responsibility for reducing greenhouse gases down to the decision makers—cities in the case of land use, and individuals in the case of travel and purchases.

Carbon budgets could be an effective way to focus the attention of local governments on greenhouse gases. Historically, localities haven't routinely considered the climate change implications of their decisions (although many voluntary initiatives have sprouted in recent times).[26] Those decisions have often encouraged sprawled development and car dependence.

In the United States, local governments control land use and jealously guard that right, without full regard for greenhouse gas emissions. Local decisions to build a new road, approve a new development, or change zoning rules are mostly related to tax considerations and the financial influence of developers. If carbon budgets were established, local governments might gravitate to infill development, greater density around transit stations, and land development patterns that support the use of neighborhood vehicles and walking.

Local carbon budgets are one approach that could help balance energy and environmental goals. California enacted a law in late 2008, known as SB375, to do just that. The law in California imposes a target on each metropolitan area that requires a fixed per capita percent in GHG emissions. The California law does not have strong carrots or sticks—yet. But full implementation of this carbon budget concept would motivate cities and counties to use pricing, public transportation investments, and land use policy to reduce vehicle use.[27] Each local government and land use decision would be analyzed to determine the greenhouse gas impact. Initially, the focus should be on carrots, not sticks, since most cities are strapped for funds. If they stay under budget, they could either bank their savings toward future use or receive bonus funds to subsidize low-carbon transport modes. Special provisions could also be available for lower-income communities that have less ability to meet carbon budget constraints.

A more radical approach is to impose carbon budgets on individuals or households. The idea is for consumers to create budgetary rules to guide their everyday behavior using dual currencies—dollars and carbon units. Tracking their energy use and carbon emissions on a routine basis makes consumers conscious of the impacts of their decisions. Once they know when and where they expend carbon, consumers are better equipped to fashion solutions tailored to their individual lifestyles.

The first foray into this arena is in the United Kingdom. Here, Environment Minister David Miliband unveiled a plan to introduce individual carbon budgets. All citizens would be allocated an identical annual carbon allowance, which would be stored on an electronic card. Consumers would decide how to meet their budgets. Those exceeding the annual allowance would have to buy credits to balance their budget from those who managed to live under budget. Such plans could be an important aspect of valuing carbon and building consumer action and markets around future climate change policies.

It will take some time for consumers to become comfortable with the idea of carbon budgets, but some fringe groups are already adopting such a plan voluntarily.[28] Robust systems that include banking and trading carbon credits may become popular and find their way into online markets, providing value to their owners.

Create incentives to advance new mobility options and enhanced regulation of transit

In the United States, departments of transportation from the local to the national level focus primarily on cars and highways, secondarily on conventional bus and rail, and very little on innovative alternatives (other than bike paths, for which there's now a small pot of federal funding in the United States). Government agencies have implemented funding systems and tend to have mindsets that ignore and are even hostile to alternative mobility services. Cities, which might be more inclined to experiment with innovative services, usually have tight budgets and little expertise. Furthermore, conventional transit services, most of them plucked out of bankruptcy by local governments in the 1960s or earlier, generally operate as monopolies. It's now clear that such an anticompetitive approach isn't always in the public interest. Transit operators have become ossified and even more resistant to disruptive innovations than large corporations.

Regulations and incentives must be used to restructure transit operations and to encourage competition and invite a broader array of mobility services. Anachronistic rules must be eliminated. Further, those privatized services that meet low-carbon standards and other overall societal goals should be eligible for public transit subsidies.

Research, develop, and test new mobility services

Perhaps the greatest transportation research need is in the area of new mobility services. Ironically, the core technologies are those favored by venture capitalists—technologies linked to the processing of information. These innovative mobility services have been largely ignored so far because investors are scared off by the conservative transit monopolies that resist innovation and competition, and the huge government subsidies for incumbent transit services.

Developing software and hardware technologies is the easy part of launching new mobility services. Innovative communications needed to support new mobility services dovetails well with current research on the interface between computers, the human brain, and decisionmaking. But because there's so little experience with these types of mobility services, the challenge is less technological and more related to designing, marketing, and financing. More research is needed to answer the following questions:[29] Who are the early markets for new mobility services—commuters, college students, city dwellers, disabled persons, retirees? How should smart paratransit and dynamic ridesharing services be designed? Is faster service more important than price, how many transfers might travelers accept, and how should personal security be protected? How might these services differ at different times and places—in cities versus suburbia, winter versus summer, poor versus rich communities? And what business models will be most effective? Will subsidies be needed? Who will provide them? How will these services interface with conventional transit services?

The challenge is to create a compelling vision of innovative mobility services and to highlight successful innovations so that state and national governments and transportation agencies, as well as private foundations and ventures, will provide funds to study, design, and advance mobility options.

Develop and test strategies and policies to motivate low-carbon behavior

In the end, scientists, engineers, and companies can produce very efficient, low-carbon, and even inexpensive new mobility options, but if no one buys or uses them, then all is for naught.

The research world has little understanding of low-carbon travel behavior. What's the demand for new forms of mobility such as smart paratransit or dynamic ridesharing? Who might purchase an alternative-fuel vehicle? What would be the effect of different incentives on vehicle purchase and usage? And how might these behaviors vary across age and social class, and across countries and specific land use patterns? Behavioral science research could play a central role in guiding the transformation of transportation.

There's growing awareness that cars and fuels are much more than technological puzzles, and that they elicit highly emotional reactions that must be better understood if transport habits are going to be altered. Behavioral research can be conducted to test strategies that motivate low-carbon habits, with the understanding that behavior is cultural. Americans differ in their lifestyles, beliefs, preferences, and attitudes from those in the EU, China, Brazil, or Russia. Developing a better understanding of evolving behavior patterns worldwide can help inform low-carbon policy design and implementation.

Realizing the Vision

As we head toward a future world of increasing vehicle ownership, innovative strategies are needed to transform behavior, vehicles, and fuels. We can look to innovative policymaking in California for new ideas on how to proceed. We can invoke novel ways to stimulate China and other awakening giants to be part of the solution and not part of the problem. We can align incentives to motivate consumers to act for the greater public good. We can rewrite the rules so local governments make decisions that further low-carbon transportation options. And we can invite entrepreneurs to develop the needed transformations in transportation.

Indeed, the first transformation, that of vehicles and fuels, is already under way, albeit tentatively. It will take many years for this transformation to play out. It will undoubtedly happen in surprising ways, calling for open-ended policy approaches that don't pick winning technologies but instead establish fair but tough, escalating goals. The second stage of the transportation revolution, a complete rethinking of how we move about, will evolve more slowly. Both transformations will require incentives, mandates, research, and demonstrations.

Change will happen. The days of conventional cars dominating personal mobility are numbered. There aren't sufficient financial and natural resources, or climatic capacity, to follow the patterns of the past. Consumers, governments, and companies all have essential roles to play in making the needed changes. The sooner we get on with addressing the issues, the better. And a durable framework is a better approach than the haphazard and ad hoc road we've been on. Adopting a strategic, long-range view is the key.

The road to surviving and thriving is paved with low-carbon fuels and electric-drive vehicles, new mobility options, and smarter governance. Enlightened consumers, innovative policymakers, and entrepreneurial businesses worldwide can drive us to a sustainable future.

Endnotes

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[1] This paper is based on Chapter 9 of D. Sperling and D, Gordon, *Two Billion Cars: Driving Toward Sustainability* (Oxford University Press, 2009).
[2] Deborah Gordon is an independent consultant in Charlottesville, VA.
[3] A wide variety of books and papers examine future vehicle technology. For future scenarios, see David McCollum and Christopher Yang, "Achieving deep reductions in US transport greenhouse gas emissions: scenario analysis and policy implications," *Energy Policy* (2010). For detailed analyses of future vehicle technologies, see various papers and reports by John Heywood and colleagues at MIT, including Andreas Schäfer, John B. Heywood, Henry D. Jacoby and Ian A. Waitz, *Transportation in a Climate-Constrained World* (MIT Press, 2009). Also, see Sperling, D and Deborah Gordon, "*Advanced Passenger Transport Technologies*," *Annual Review of Environment and Resources*. 2008. 33:63–84; and Chapter 2 ("Energy Efficiency in Transportation"), National Research Council, *Real Prospects for Energy Efficiency in the United States,* America's Energy Future Panel on Energy Efficiency Technologies (National Academy Press, 2009).
[4] William J. Mitchell, Christopher E. Borroni-Bird and Lawrence D. Burns, *Reinventing the Automobile: Personal Urban Mobility for the 21stCcentury* (MIT Press, 2010).
[5] See National Research Council, *Real Prospects for Energy Efficiency in the United States, America's Energy Future Panel on Energy Efficiency Technologies*, National Academy Press, 2009; and Burton Richer, David Goldston, George Crabtree, Leon Glicksman, David Goldstein, David Greene, Dan Kammen, Mark Levine, Michael Lubell, Maxine Savitz, and Daniel Sperling, *Energy Future: Think Efficiency*. American Physical Society, Washington, DC, September 2008, 107pp. www.aps.org/energyefficiencyreport
[6] David Greene, John German, and Mark Delucchi, "Fuel Economy: The Case for Market Failure," in Dan Sperling and James Cannon, eds., *Reducing Climate Impacts in the Transportation Sector* (Dordrecht, NL: Springer, 2008).
[7] See Anthony Grezler, "Heavy Duty Vehicle Fleet Technologies for Reducing Carbon Dioxide: An Industry Perspective," in Dan Sperling and James Cannon, *Climate Policy for Transportation* (Dordrecht, NL: Springer, 2008); J. Leonardi and M. Baumgartner, "CO_2 Efficiency in Road Freight Transportation: Status Quo, 45 Measures and Potential," *Transportation Research*, Part D, 9 (2004): 451–64; A. Vyas, C. Saricks, and F. Stodolsky, *The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks,* Argonne National Laboratory ANL/ESD/02-4 (2002).
[8] International Energy Agency and International Transportation Forum, *Fuel Efficiency for HDVs, Standards and Other Policy Instruments: Towards a Plan of Action*, Paris, France (2007). For an expanded description of the Japanese program, see the untitled final report (translated from Japanese) prepared by the Heavy Vehicle Fuel Efficiency Standard Evaluation Group, Heavy Vehicle Standards Evaluation Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy. http://www.eccj.or.jp/top_runner/pdf/heavy_vehicles_nov2005.pdf.
[9] This carbon performance standard would actually be a life-cycle greenhouse gas standard. See D. Sperling and Sonia Yeh, "Toward a Global Low Carbon Fuel Standard," *Transport Policy,* 17 (2010) 47–49. Also see Alexander Farrell and Daniel Sperling, *A Low-Carbon Fuel Standard for California, Part 1: Technical Analysis*, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-07-07 (2007); and Alexander Farrell and Daniel Sperling, *A Low-Carbon Fuel Standard for California, Part 2: Policy Analysis*, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-07-08 (2007).
[10] As discussed in Chapter 5, we're lukewarm on cap-and-trade policies. But since this approach is gaining momentum, and because it's important to send a consistent signal to the entire economy, we think economywide cap-and-trade programs are worth pursuing. The principal reason to support cap-and-trade programs for the transport sector would be to generate a huge revenue stream from the sale of the carbon allowances to oil refineries—in the billions of dollars per year in the United States and Europe.
[11] Heleen de Coninck, Carolyn Fischer, Richard G. Newell, and Takahiro Ueno, "International Technology-Oriented Agreements to Address Climate Change," *Energy Policy* 36 (2007): 335–56.

[12] CNNMoney.com, April 2009, http://money.cnn.com/2009/04/13/technology/gunther_electric.fortune/.

[13] For a more extensive discussion of each of these fiscal and other policies see Deborah Gordon, *Steering a New Course: Transportation Energy and the Environment* (Washington, DC: Island Press, 1991); OECD, *Policy Instruments for Achieving Environmentally Sustainable Transport*, Organization for Economic Co-Operation and Development, Paris (2002); Y. Hayashi, H. Kato, R. Val R. Teodoro, "A Model System for the Assessment of the Effects of Car and Fuel Green Taxes on CO2 Emissions," *Transportation Research* Part D, 6 (2001): 123–39; and D. L. Greene, P. D. Patterson, M. Sing, and J. Li., "Feebates, Rebates and Gas-Guzzler Taxes: A Study of Incentives for Increased Fuel Economy," *Energy Policy* 33 (2004): 721–827.

[14] U.S. initiatives include a limited gas-guzzler tax on cars (not light trucks) and some incentives for hybrid vehicles. For elsewhere, see Japan Automobile Manufacturers Association (JAMA), *The Motor Industry of Japan 2007*, May 2007; Transport Canada, Budget 2007, *Eco Transport Vehicle Eligibility*, 2007; Government of Ontario, Ministry of Finance, 2007, *Tax for Fuel Conservation (TFFC)*; ACEA 2007.

[15] Association of European Automobile Manufacturers (ACEA), *2007 Tax Guide*, January 2007.

[16] 5000 € was equivalent to $US 7800 in spring 2008. See "France to Institute Vehicle Feebate Based on CO_2 Emissions," www.greencarcongress.com, December 7, 2007, based on an announcement by the Ministry of Ecology (Ministère de l'Ecologie, de l'Energie, du Développement durable et de l'Aménagement du territoire).

[17] The feebate concept was first developed in D. Gordon and L. Levenson, "DRIVE+: Promoting Cleaner and More Fuel-Efficient Motor Vehicles Through a Self-Financing System of State Tax Incentives," *Journal of Policy Analysis and Management* 9 (1990): 409–15.

[18] The analysis assumed that fees and rebates would be no larger than $2500 per vehicle, the zero band (those vehicles neither charged nor rebated) would include 20 to 25 percent of vehicles, and the tariff schedule would be structured to be revenue neutral. See Walter McManus, "Economic Analysis of Feebates to Reduce Greenhouse Gas Emissions from Light Vehicles for California," University of Michigan Transportation Research Institute, UMTRI-2007-19-1 (2007).

[19] W. B. Davis, M. D. Levine, K. Train, and K. G. Duleep, *Effects of Feebates on Vehicle Fuel Economy, Carbon Dioxide Emissions, and Consumer Surplus*, DOE/PO-0031 (Washington, DC: Office of Policy, U.S. Department of Energy, 1995).

[20] Progressive Insurance Company piloted PAYD insurance in Texas, using global positioning satellite (GPS) technology. Another pilot project is being launched in Georgia, with funding from the Federal Highway Administration's Value Pricing Program. Oregon, Washington, Massachusetts, and other states are also working toward PAYD. In the United Kingdom, Norwich Union has become the first insurer to offer PAYD.

[21] Donald Shoup, *Parking Cash Out* (Chicago: Planning Advisory Service, 2005).

[22] Donald C. Shoup, "Evaluating the Effects of Cashing Out Employer-Paid Parking: Eight Case Studies," *Transport Policy* 4 (1997): 201–16.

[23] The U.S. Environmental Protection Agency is also attuned to the fuel savings associated with smoother driving, which it estimates can improve fuel economy by as much as one third.

[24] Reported by G. Lenaers (Vehicle Technologies, VITO-Belgium) at the 17th CRC On-road Vehicle Emissions Workshop, San Diego, California, March 26–28, 2007. The study defined eco-driving as shifting gears to lower engine speeds, reducing acceleration speeds, using cruise control, and anticipating slowdowns. The similar "relaxed" style involved accelerations of 0.45 to 0.65 m/s2 on urban and rural roads, while aggressive driving involved accelerations of 0.85 to 1.1 m/s2. At a 2006 OECD workshop on eco-driving, Martin Kroons, a former eco-driving instructor for the Dutch government, reported that advanced eco-driving can reduce fuel consumption for an individual by up to 25 percent.

[25] According to the United Nations Development Programme, which is calling on the U.S. to adopt carbon budgets, the 19 million residents of New York State have a bigger carbon footprint than the 766 million people living in the world's fifty least developed countries. And the average American car emits nearly ten times more carbon dioxide in a year than a person in Afghanistan or Cambodia during his or her lifetime. United Nations, Human Development Report, "Fighting Climate Change: Human Solidarity in a Divided World," 2007.

[26] Lutsey and Sperling, "America's Bottom-Up Climate Change Mitigation Policy."

[27] For fuller development of the concept of city carbon budgets, see Deborah Salon, Daniel Sperling, Alan Meier, Roger Gorham, Sinnott Murphy, and James Barrett, “City Carbon Budgets: A Proposal to Align Incentives for Climate-Friendly Communities,” *Energy Policy*, volume 38, issue 4, 2010, pp. 2032 – 2041.
[28] James Kanter, “Groups’ Aim: The Greening of Britain,” *New York Times*, October 21, 2007.
[29] For an early review of the challenges and opportunities, see the following report on a 1999 conference held on this topic: D. Salon, D. Sperling, S. A. Shaheen, and D. Sturges, *New Mobility: Using Technology and Partnerships to Create More Sustainable Transportation*, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-99-01 (1999). Since then, Dr. Susan Shaheen developed and directed a program on “innovative mobility services” for the California Partners for Advanced Transit and Highways (PATH), a research center of the University of California largely supported by the California Department of Transportation. Various research initiatives have emerged elsewhere, but none have gained widespread attention or resources.

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