OPPORTUNITIES AND CHALLENGES OF A NO-REGRETS RESEARCH AND DEVELOPMENT PROGRAM FOR ADVANCED VEHICLE TECHNOLOGIES

James Kliesch

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1001 Connecticut Avenue, NW, Suite 801, Washington, D.C. 20036
202-429-8873 phone, 202-429-2248 fax, www.aceee.org Web site

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EXECUTIVE SUMMARY

Advanced vehicle technologies have the potential to ease many of the environmental and political challenges associated with U.S. petroleum demand. Extracting the United States from dependence on Middle Eastern oil, mitigating the sources of climate change, and improving regional air quality are a few of the major objectives that could in part be served through greater use of alternative vehicle technologies.

Hydrogen fuel cell vehicles have been characterized as a long-term solution to these challenges by many, including members of Congress and the White House. However, a successful transition to a hydrogen-based transportation system is a complex and uncertain endeavor, as a daunting number of economic, technical, and logistical hurdles must first be overcome. Considering the multi-dimensional challenges facing hydrogen and fuel cell vehicle development, significant market penetration of hydrogen vehicles is decades away, even under the most promising technology development scenario.

Over the past fifteen years, a number of energy initiatives have been developed aimed at reducing costs and minimizing market barriers for promising near-term vehicle technologies as well. Hybrid-electric vehicles, plug-in hybrid-electric vehicles, and flexible fuel vehicles capable of running on cellulosic ethanol, for example, all offer promise in reducing oil consumption, cutting GHG emissions, and improving local air quality. Yet these technologies, too, will require proper nurturing before becoming a practical alternative to today’s conventional internal combustion engine vehicles.

In light of these challenges, and given the limited funds (both public and private) available for vehicle and fuel RD&D, development of effective vehicle technologies calls for a strategic approach. Governmental entities allocating limited funds for research, development, and demonstration projects can make their investments go further by prioritizing the technologies that simultaneously build a path toward commercialization of fuel cell vehicles *and* increase the viability of other, more near-term vehicle technologies emerging today.

Resources spent on technologies and fuels that support multiple pathways to environmentally preferable vehicles rather than a single such pathway can be “no-regrets” investments. These are investments in technology areas that move vehicles toward the goal of dramatically reduced environmental impacts, without requiring advanced knowledge of what vehicle and fuel will ultimately prevail.

Fortunately, many of the research areas related to these technologies have such potential, making them wise investment candidates. Energy storage devices (such as advanced batteries and ultracapacitors), power electronics, vehicle electrification, lightweight materials, and parasitic loss reduction are a handful of the technologies that offer potential in this capacity. These components can be utilized in a number of promising energy-saving advanced vehicle designs, including hybrid-electric vehicles, plug-in hybrids, electric vehicles, and in some cases, even advanced conventional vehicles as well. By prioritizing research funding toward overlapping technology areas such as these, one supports the evolution of vehicle technology without having to choose winners and losers.

Recent policy discussions on the topic of vehicle efficiency and advanced vehicle technologies have characterized the options as having an either/or relationship; fuel economy standards have come under fire for adversely impacting automakers' abilities to pursue longer-term advanced vehicle technologies. As this report demonstrates, advances in certain technologies can boost efficiencies in near-term vehicles, while simultaneously furthering longer-term transportation energy objectives.

The challenges facing this nation's transportation sector are so substantial that no single technical solution exists. A portfolio of technologies, including hybrid-electrics, plug-in hybrids, vehicles operating on low-carbon biofuels, and efficient conventional vehicles will all play an important role in a multi-pronged strategy toward reduced oil dependency. By focusing on a no-regrets approach to research and development, we can attain the benefits of clean and efficient near-term technologies without abandoning our longer-term sustainable transportation goals.

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INTRODUCTION

Transportation trends, particularly those related to passenger vehicles, are a continuing cause for concern. Roughly 230 million vehicles are on the road in the United States at this time, with the sale of 17 million new vehicles each year. Fuel economy of new passenger vehicles has stagnated for the past two decades as the market share of less efficient light trucks increased from 28 percent in 1986 to more than 50 percent in 2006 (EPA 2006). Meanwhile total vehicle miles traveled (VMT) continues to grow, with passenger vehicles alone exceeding 2.65 trillion vehicle miles annually (EIA 2007a). The consequence of these trends has been a 35 percent increase in energy use of automobiles and light trucks between 1986 and the present (Davis and Diegel 2007). This thirst for oil contributes to a number of complex challenges: dependence on imported oil, global climate change, and local air pollution.

Notable increases in passenger vehicle fuel economy would go a long way toward mitigating these challenges. Similarly, successful development and penetration of advanced vehicle technologies and/or alternative energy sources in the passenger vehicle market could offer a range of opportunities to curb oil consumption. Recent policy discussions on the topic of vehicle efficiency and advanced vehicle technologies, however, have characterized the options as having an either/or relationship. Fuel economy standards have come under fire for adversely impacting automakers' abilities to pursue advanced vehicle technologies; policymakers have argued that manufacturer costs incurred to address near-term increases in average fuel economy standards would limit manufacturers' abilities to develop advanced vehicle technologies (see, e.g., Bond et al. 2005). The reality, however, is far different. Long-term advanced technologies such as hydrogen fuel cell vehicles share numerous components with other, more near-term options that, if applied, could improve vehicle fuel economy, reduce oil dependence, cut greenhouse gas emissions, and improve local air quality.

However, a successful transition to long-term advanced vehicle technologies is a complex and uncertain endeavor, since numerous economic, technical, and logistical hurdles must first be overcome. In light of this uncertainty, and given the limited funds (both public and private) available for vehicle and fuel RD&D, development of these technologies calls for a strategic approach.

Resources spent on technologies and fuels that support multiple pathways to environmentally preferable vehicles rather than a single such pathway can be "no-regrets" investments.[1] These are investments in technology areas that move vehicles toward the goal of dramatically reduced environmental impacts without requiring advanced knowledge of what vehicle and fuel will ultimately prevail. The following report examines the opportunities and challenges of a research and development program for such technologies.

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[1] Note, the definition of "no regrets" throughout this report applies to technology pathways and should not be confused with climate change "no-regrets options" that pertain to mitigation options with negative net costs.

Oil Dependence

For the past two decades, the United States has been responsible for about one-quarter of the world's petroleum consumption. In the same period of time, the U.S. share of global crude production dropped from approximately 16 percent to 7 percent. Estimates of current world oil reserves place the United States at 2 percent, while OPEC and the rest of the world account for 70 percent and 28 percent, respectively (Davis and Diegel 2007). In the absence of an alternative to oil, a demand for oil imports from a global market heavily affected by OPEC actions and Middle East geopolitics has fashioned an increasingly problematic dependence on the region. Oil prices exceeded $75 per barrel in the summer of 2006, and U.S. consumers found themselves at the mercy of both real and perceived threats to a steady oil supply, resulting in average pump prices above $3.00 per gallon.

Oil price shocks resulting from petroleum dependence have multiple major economic impacts, including (Greene and Ahmad 2005):

- Output levels of produced goods are reduced as a result of the relative increase of energy costs, affecting potential gross domestic product levels
- Sudden price disruptions set the economy into an imbalance, increasing unemployment and further reducing produced goods
- Wealth from the United States is transferred to foreign oil-producing countries

A transportation system based on vehicle efficiency technologies and alternative fuel sources has the potential, in time, to reduce U.S. dependence on foreign oil. Efficient technologies — especially those utilizing sustainable, renewable energy sources — would help enable domestic energy sources to supplant imported fuel.

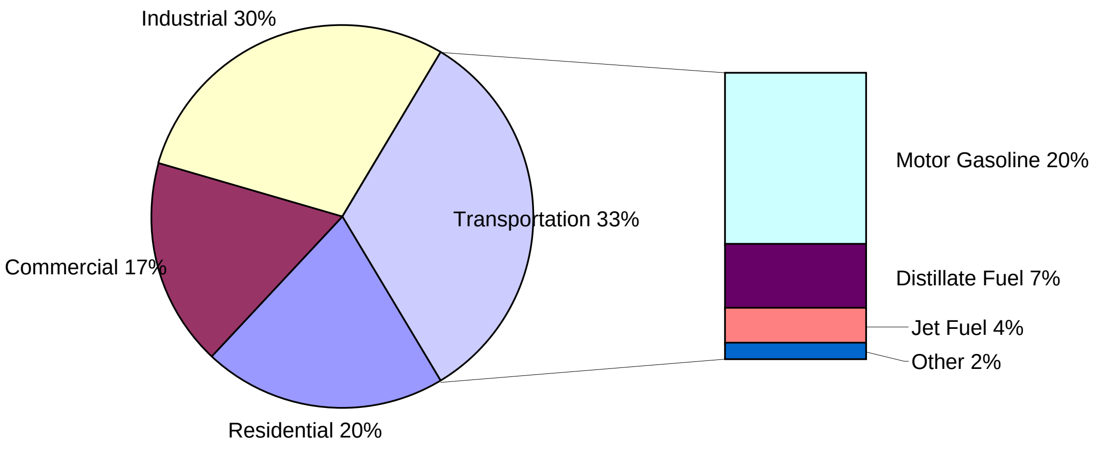
Global Climate Change

In 2004, the United States emitted 5,923 million metric tons of carbon dioxide, accounting for 44 percent of OECD CO_2 emissions and 22 percent of global CO_2 emissions. Of those emitted by the United States, more than 43 percent (2,598 million metric tons) resulted from oil use (EIA 2007b). As shown in Figure 1, the transportation sector is responsible for approximately one-third of this country's annual CO_2 emissions attributed to fossil energy consumption, while gasoline accounts for sixty percent of transportation's GHG emissions (EIA 2006a).

As demonstrated by these statistics, any meaningful effort to minimize the impacts of global climate change must address passenger vehicles in the United States. While numerous technologies with the potential to improve vehicle efficiency are entering the marketplace (such as variable valve timing, cylinder deactivation, continuously variable transmissions, advanced diesel powertrains, etc.), automotive industry trends over the past thirty years suggest that, absent new federal policies to ensure energy savings, technologies will be used merely to offset the production of faster, more powerful vehicles.

The climate change impact of a transition to alternative fuels such as hydrogen, ethanol, or electricity depends largely on the feedstock type and production methods of the alternative fuel. For example, with respect to hydrogen, the National Research Council concluded "the use of coal without sequestration or of distributed electrolysis using grid-supplied electricity would lead to little or no further reductions in CO_2 releases than would occur through a transition to [gasoline hybrid-electric vehicles]" (National Research Council 2004). Similarly, carbon dioxide emissions associated with plug-in hybrid-electric vehicles would also vary substantially, depending on the fuel mix utilized to generate electricity supplied to the vehicle (Kliesch and Langer 2006). Furthermore, absent widespread adoption of nuclear- or renewable-based electricity generation, or technological solutions such as carbon capture and sequestration, such variation in regional carbon emissions will persist.

Figure 1. 2004 CO_2 Emissions Related to U.S. Fossil Energy Consumption, by Sector and Fuel



Local Air Pollution

National emissions of major criteria pollutants have notably decreased over the past thirty years. However, the transportation sector still accounts for the majority of both carbon monoxide and nitrogen oxide emissions in the country, and plays a major role in emissions of other pollutants as well. Within the transportation sector, passenger vehicles contribute significantly to emissions of major pollutants. In 2002, passenger vehicles[2] were responsible for 52 percent of total national CO emissions, 17 percent of NO_x emissions, and 25 percent of VOC emissions (EPA 2005).

While national ozone concentrations are on a slow-but-steady decline, EPA recently designated 474 counties in 31 states across the country as nonattainment areas for the 8-hour ozone standard. These air quality issues affect the health of millions of people each year, as well as their surrounding ecosystems. Responsible for a host of respiratory ailments, ozone is generated from precursor pollutants emitted by passenger vehicles, among other sources.

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[2] Includes cars, light trucks under 8,500 lbs. GVW, and motorcycles.

Alternative vehicle fuels and technologies such as hydrogen fuel cells, plug-in hybrids, and ethanol-powered vehicles have the potential to offer a dramatic reduction of in-use emissions compared to today's passenger vehicle fleet. Major emissions challenges associated with these technologies are in the upstream phase (including production of hydrogen or ethanol, and generation of electricity) and will vary, as they are highly dependent upon production methods and feedstock sources. Certain alternative technologies could face emissions challenges that arise as a result of their operational design. A plug-in hybrid, for example, which by design only periodically engages its internal combustion engine, could face emissions challenges related to retaining proper heating of the catalyst during its electric operation. Still, the potential of advanced, alternative vehicle technologies to reduce in-use emissions on the whole suggests they could play an important role in minimizing the environmental impact of motor vehicles.

PRESIDENTIAL INITIATIVES

In January 2003, President Bush unveiled the Hydrogen Fuel Initiative, a program which, in conjunction with the government-industry FreedomCAR Partnership, promoted the development of cost-effective hydrogen fuel cell vehicle technologies, as well as the supporting technologies for production, storage, and delivery of hydrogen fuel. At that time, it called for an investment of $1.2 billion between 2004 and 2008, with a goal of making hydrogen fuel cell vehicles cost effective and widely used in the United States by 2020.

Three years after the Hydrogen Fuel Initiative announcement, President Bush declared a national goal of replacing more than 75 percent of the nation's Middle East oil imports by 2025. In accordance with this goal, he unveiled the so-called Advanced Energy Initiative, a multi-pronged approach to reducing U.S. dependence on foreign energy sources (The White House National Economic Council 2006). Subsequent statements by senior administration officials, however, indicated that the proposed initiative's objective was not to reduce the amount of imports per se, but rather to reduce projected 2025 U.S. consumption levels by 5.26 million barrels per day (The White House 2006). This amounts to slightly less than half of the 11.25 million barrels per day projected to be consumed by light duty vehicles at that time (EIA 2007a).

The Advanced Energy Initiative sought to curb both transportation and home energy use, and was supported by a 22 percent increase in funding for clean energy technologies in those areas. The initiative's transportation element focused largely on the development of alternative fuel sources for vehicles. Notably, it included:

(1) $31 million (a 27 percent increase) in funding to support advanced battery technology research that would, in turn, enable production of plug-in hybrid-electric vehicles capable of achieving a 40-mile electric-only operating range goal.

(2) $150 million (a 65 percent increase) in funding to support research and development of cellulosic ethanol. The initiative included a goal of making cellulosic ethanol cost-competitive with corn-based ethanol by 2012.

(3) $196 million (a 26 percent increase) in funding to support both hydrogen fuel and hydrogen vehicle technology research, in order to help meet the Hydrogen Fuel Initiative goal, with particular focus on fundamental materials science research to attain solutions for hydrogen storage challenges.

However, Advanced Energy Initiative funding increases were made with the concurrent elimination of federal funding for geothermal and hydro energy research in the FY 2007 budget request[3], as well as the reduction of funding for distributed energy resources, weatherization, and industrial energy conversion, among others (DOE 2006c). As such, the net energy savings impact of the federal redirection was less than the particular program budget increases suggested.

In January 2007, the administration announced its “20-in-10” plan, with a goal of displacing 20 percent of annual gasoline use by 2017 through renewable and alternative fuel production increases, as well as increases in passenger vehicle fuel economy. A closer examination of this initiative, however, found its alternative fuel goals ill-defined and of questionable feasibility, while its vehicle fuel economy goals eminently achievable (ACEEE 2007). This latest initiative does signal a continued interest in non-petroleum fuels, and ethanol in particular. More generally, the three Presidential energy initiatives noted above signal, in the area of advanced vehicle technologies and fuels, a strong interest in the development of plug-in hybrid-electric vehicles, ethanol-powered vehicles, and hydrogen-powered fuel cell vehicles.

Plug-In Hybrid-Electric Vehicles

Plug-in hybrid-electric vehicles (PHEVs) are a recent transportation technology development garnering much attention for their potential to cut oil consumption. Bridging the gap between pure battery-electric vehicles (EVs) and hybrid-electric vehicles (HEVs), plug-in hybrids allow for a modest amount of electric-only travel, without the range limitations that face EVs. The primary differences between HEVs and PHEVs are the battery type and size, battery logic/utility, and source of electricity stored on the vehicle.

While HEVs generate all of their needed electricity onboard the vehicle, PHEVs contain a larger battery pack that can be recharged through the electricity grid. The larger battery enables greater electric-only use, theoretically cutting down on in-use emissions[4] and supplanting a portion of petroleum-based travel with electric grid-based travel. While PHEVs could offer significant advantages over today’s HEVs, their success will require important advances in the areas of battery cost, durability, and safety. Furthermore, in order to fully realize the environmental potential of PHEVs, dramatic reductions in power plant emissions (including carbon emissions) must be implemented (Kliesch and Langer 2006).

Because of the potential for reduced petroleum consumption associated with PHEV market penetration, development of batteries and other components meeting PHEV performance,

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[3] Funding levels were subsequently reinstated in the FY 2007 continuing resolution.

[4] One of the emissions challenges facing PHEVs is how to address continued “cold start” exhaust levels due to frequent inactivity of the internal combustion engine.

cost, durability, and safety objectives is one of the Energy Department's primary vehicle technology objectives. DOE is currently soliciting competitive technology development awards for PHEV components, and an aggressive collaborative agenda for helping bring PHEVs to market has been detailed (DOE 2007a). In addition to helping meet the goal of reducing consumption of foreign oil and improving the United States' energy security, it is likely that successful implementation of PHEVs will in part shift emissions from many widely dispersed vehicle tailpipes to a more modest number of power plant smokestacks. As such, widespread adoption of renewable energy-based electricity generation could cut total emissions of plug-in hybrids even further.

Despite the promise of plug-in hybrid-electric vehicles, at this time a number of technical hurdles must still be surpassed for the technology to fully realize its potential. Nearly all of these challenges are related to PHEV batteries. Minimizing battery cost, size, and weight; improving battery performance, cycle life, calendar life, and abuse tolerance; and improving battery safety with respect to manufacturing flaws, crash protection, and overcharge protection are all critical to the success of plug-in hybrid technology.

Important improvements in battery technology have been made during the past few years. Specific power, specific energy, and battery lifetimes, for example, have seen advancements, as has the durability of NiMH batteries. However, to date, advanced vehicle batteries have largely been used in modest power-assist modes (as currently used in HEVs) and employed using NiMH chemistries.

The demanding battery performance specifications for PHEVs will require carefully balanced attention to cost, weight, volume, and operational design. Meeting the President's call for a vehicle that provides a 40-mile electric-only range (PHEV40) would likely necessitate the use of lithium-ion batteries. The cost, volume, and weight associated with a NiMH battery pack capable of providing that range would be unfeasible in a passenger vehicle. The use of lithium-ion batteries would enable a smaller and lighter battery pack, though cost challenges would persist. Since deep discharging shortens a battery's useful life, a vehicle with a 40-mile range would require either a larger battery pack — effectively minimizing deep discharges for a comparable amount of energy — or battery replacement during the vehicle's life. Given the cost of advanced batteries, neither of these options seems viable. A more feasible option would be to reconfigure the vehicle's operating strategy. Rather than providing, for example, 40 miles of electric-only operation, the vehicle's internal combustion engine would regularly engage to support the electric motor in meeting the driver's needs (Markel and Simpson 2006). This "blended" strategy would not only save fuel relative to a conventional vehicle, but also preserve the battery lifetime and avoid the need for replacing such a key, expensive component.

Cellulosic Ethanol

Alternative fuels, particularly ethanol and other bio-based fuels, have seen a strong resurgence of interest in the past few years. Cellulosic ethanol, regarded as a more environmentally favorable type of ethanol, is alcohol derived from cellulosic biomass sources such as corn stalks and leaves, grasses, tree limbs, woodchips, discarded wood and paper products, and vegetation grown specifically for the purpose of creating alcohols. Municipal solid waste, another feedstock option, contains certain cellulosic materials such as paper. Cellulosic ethanol is made by breaking down cellulosic material into its component sugars, and then fermenting the sugars into alcohol. This type of ethanol offers great potential as a domestic source of transportation energy, though a number of technical hurdles remain before it can be produced at a competitive price.

At this time, the only mass-produced biofuels in the country are biodiesel and corn-based ethanol. Biodiesel sees limited use, with 2005 production of only 75 million gallons. Production of ethanol, by comparison, was more than 3,900 million gallons that same year (Moran 2006; RFA 2006).[5] Approximately 30 percent of gasoline sold in the U.S. today contains ethanol as a fuel additive (in concentrations of roughly 10 percent or less); by volume, ethanol accounts for about 3 percent of all gasoline sold in the country (Jennings 2005). In certain regions (particularly the corn-growing Midwest states), ethanol is available in a higher concentration, E85 (an 85 percent ethanol/15 percent gasoline blend), for use in flex-fuel vehicles. Ethanol is expected to see increased domestic use in the coming years, as a result of an excise tax credit ($0.51/gallon of motor fuel ethanol) and a mandate in the 2005 Energy Policy Act specifying the use of at least 7.5 billion gallons of renewable fuel in gasoline by 2012 (U.S. Congress 2005).

Despite these projections, corn ethanol faces volume constraints in terms of both available land and competing uses for corn. According to the National Corn Growers Association, between 12.8 and 17.8 billion gallons of corn-based ethanol could be produced in 2015 (NCGA 2006). By volume, this amounts to between 8.2 and 11.5 percent of the projected 10.13 million barrels per day of oil equivalent projected to be consumed that year (EIA 2006b). An increased percentage of ethanol use in vehicles domestically will require improved vehicle efficiency, growth of a cellulosic ethanol market, or both.

Although using corn-based ethanol to fuel our vehicles will yield certain emissions and energy independence advantages over gasoline, the potential benefits of cellulosic ethanol are far greater than those of ethanol produced from corn. According to a recent Argonne National Laboratory lifecycle analysis, corn ethanol on a per-gallon basis reduces GHG emissions 15–26 percent from a gasoline vehicle baseline, while cellulosic ethanol reduces GHG emissions 87 percent from the baseline. While corn and cellulosic ethanol each call for only small amounts of petroleum to be utilized in its production (roughly 0.1 Btu of petroleum per 1.0 Btu of ethanol at the pump, in each case), producing corn ethanol requires an additional 0.64 Btu of natural gas and coal energy. In comparison, producing cellulosic ethanol requires less than 0.1 Btu of additional natural gas and coal energy (Wang and Santini 2006). In other words, cellulosic ethanol requires only one-fourth the amount of fossil fuel for its production compared to corn-based ethanol. Given the significant GHG and fossil energy benefits of cellulosic ethanol, corn-based ethanol should be viewed primarily as a stepping stone to a cellulosic ethanol market.

With certainty, numerous challenges still face a scenario in which cellulosic ethanol is widely used. Production of cellulosic ethanol is limited by technical challenges in extracting the

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[5] Even including the 135 million gallons of imported fuel ethanol in 2005, U.S. consumption of gasoline, at roughly 140 billion gallons each year, still dwarfs these levels.

cellulose and hemicellulose, which are fermented into alcohols, from the remaining non-carbohydrate polymers such as lignin that provide structure to the plant. Pilot and demonstration programs are currently underway to improve our understanding of the molecular processes by which cellulosic material is broken down, in order to increase efficiency and, perhaps most importantly, allow for the production of competitively priced ethanol.

As research into cellulosic ethanol progresses, attention should also be paid to possible competition between corn and cellulosic ethanol interests. Although cellulosic ethanol can be produced from corn-based feedstocks (e.g., corn stover, corn fiber), it is not a requirement. Cellulosic ethanol production can embrace a broad range of feedstocks, allowing for production facilities to be placed not merely in the cornbelt, but across the country, minimizing distribution costs. Given the range of feedstocks (and by extension, placement of facilities) considered for the production of cellulosic ethanol, this technology is sure to bring new political and business interests to the table. It is important to keep these issues in mind as cellulosic ethanol R&D progresses; given the stakes, political interests should not dictate the development of cellulosic ethanol production techniques.

In light of both the near-term demands for corn ethanol and limitations to cost-effective cellulosic ethanol production, careful thought should also be applied to how ethanol is best utilized in the near future. One idea recently proposed by MIT researchers is to employ ethanol in a unique engine design that uses modest amounts of the alcohol to offer a 20–25 percent improvement in fuel economy at comparable vehicle performance (Karagianis 2007). In this design, the fuel saving advantage of ethanol is not merely from the substitution of gasoline, but rather from the ethanol's ability to modify the combustion process in the cylinders.

The MIT design uses a downsized, turbocharged engine that receives an ethanol (or E85) injection "boost" to cool cylinder gases, thereby suppressing spontaneous combustion in the cylinders (an occurrence commonly known as engine knock). With knock concerns eradicated, efficiency can be improved through the use of higher compression ratios. Furthermore, the use of a turbocharger increases the system's power output, allowing for the use of a downsized, more efficient engine without compromising performance. The combination of the smaller, turbocharged engine and a higher compression ratio offers a significant efficiency improvement at a modest cost and inconvenience to the user. While a separate tank of ethanol (or E85) would have to be maintained by the driver, the incremental hardware cost for this system is estimated to be approximately $1,000, and the ratio of ethanol-to-gasoline consumed is only 5 percent, equating to an ethanol refill once every one to three months. Operating the vehicle without ethanol would not damage it, but would cause a temporary performance decline (Stauffer 2006). Unlike engines operating on E85, which utilize fuel substitution to offer oil savings benefits, this design has the potential to notably reduce oil consumption with modest use of ethanol. Given the cost challenges facing cellulosic ethanol, a design that sips ethanol while still offering sizable petroleum savings is a logical hardware choice to pair with a fledgling cellulosic market.

Although biofuels are not a panacea for the United States' dependence on oil, they have the potential to play an important role in a multi-pronged strategy toward reduced oil dependency (see, for example, N. Greene 2004). This effort also needs to include not only increased use of sustainable fuels, but improved efficiency of petroleum-fueled vehicles and implementation of anti-sprawl/smart growth principles in the development of communities. It bears repeating that the challenges facing this nation's transportation sector are so large that no single technical solution exists. A portfolio of activities, rather, will be essential in shifting toward a more sustainable transportation sector.

Hydrogen Vehicles

While important progress in hydrogen research has been made over the past five years, a hydrogen-based transportation system still faces a number of critical challenges. These technical hurdles can be grouped into four major categories: hydrogen production, hydrogen distribution, hydrogen storage, and automotive application.

Hydrogen Production

While hydrogen is the most abundant element in the universe, making up about 75 percent of all matter, it does not readily exist in a pure state. Rather, it is most often found as part of a compound, such as hydrocarbons or water. Because of this, it is necessary to first "reform" hydrogen gas from the alternate source. A range of hydrogen production technologies, at various stages of development, are currently being investigated. This includes, for example, steam reforming of methane (thermal production), splitting water into hydrogen and oxygen using electricity (electrolytic production), and using light energy to split water (photolytic production).[6]

The methods and compounds from which hydrogen is reformed will dramatically affect the emission and oil dependence profiles of a hydrogen fuel cell vehicle. A vehicle running on hydrogen produced from electrolysis using grid electricity (without carbon sequestration), for example, would enable the use of a domestic energy source. However, it could also emit more greenhouse gas emissions per mile driven (given the utility power plant mix) than even a vehicle with a conventional gasoline internal combustion engine (Wang and Mintz 2003).

Furthermore, questions remain about whether production facilities should be large and centralized, intermediate and semi-centralized, or small and distributed. Each of these has tradeoffs between production economies of scale and distribution costs. Absent policy incentives, production facility types can be expected to be determined by market conditions.

Hydrogen Distribution

Related to fuel production challenges is the question of hydrogen distribution. A small infrastructure of pipelines, barges, rail cars, and trucks used for the delivery and storage of hydrogen is currently in place to meet industrial uses of hydrogen gas. However, a network

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[6] For more information about U.S. Department of Energy research into hydrogen production, see http://www.eere.energy.gov/hydrogenandfuelcells/production/.

capable of supplying fuel to a significant portion of today's vehicles would likely require a notably different configuration. The optimal design will depend heavily on whether the production facilities are centralized or distributed.

Chief challenges related to hydrogen distribution include minimizing distribution costs, preserving hydrogen purity, improving energy efficiency, and reducing leakage. Further complicating hydrogen distribution is the fact that hydrogen is difficult to store; it is relatively bulky, even when compressed, minimizing the efficiency of distribution methods. Cooling hydrogen into a cryogenic state improves its energy density (allowing more of it to be transported in a given trip), but liquefaction is an expensive and energy-intensive process, requiring roughly 30 percent of the amount of energy contained by the hydrogen (DOE 2005a).

Pipelines are currently the least expensive method for delivering hydrogen in significant quantities. However, dedicated pipelines are expensive and require a substantial upfront investment. The use of existing natural gas pipelines to deliver a blend of natural gas and hydrogen may allow for cost reductions, though it also poses purity challenges.

One option currently under investigation is to produce a liquid energy carrier (such as methanol or ethanol) at a centralized facility, and process the carrier into hydrogen at the refueling station. While ethanol has its own distribution challenges, current interest in that fuel may accommodate near-term development that, in turn, opens up distribution options for a hydrogen infrastructure. Such an approach, however, would expend significant energy in the production of a liquid energy carrier and its subsequent conversion into hydrogen.

Hydrogen Storage

Storage of hydrogen is another challenge. Whether for on-board or off-board applications, developing a safe, durable, and cost-effective method of storing hydrogen will be critical to a successful hydrogen program. Hydrogen can be stored in a gaseous or liquid form, as well as on (or, in some cases, in) a solid material. Each approach has its own sets of pros and cons related to cost, sizing requirements, ease-of-use, and volumetric density.

Ultimately, in a vehicular environment, one of the most difficult storage challenges will be providing a range equivalent to today's gasoline-fueled vehicles — in the neighborhood of 300 miles. At reasonable pressures, hydrogen cannot be compressed to volumetric energy densities comparable to liquid fuels, and is at a significant disadvantage compared to a liquid fuel such as gasoline. Driving ranges for hydrogen vehicles depend on a number of factors, including vehicle type, tank size, and tank pressure. Stronger tanks allow greater range; however, they are also heavier, bulkier, and more expensive.

Automotive Application

Finally, fuel cells themselves face a number of technical challenges in the area of automotive application. Vehicles are unquestionably harsh environments, subjecting their components to a wide array of conditions, including extreme temperatures, vibration, repetitive operation, extended periods of operation, etc. Despite those conditions, vehicle components are expected to reliably meet performance requirements, as well as to be designed in a way that is compatible with other vehicle criteria (packaging constraints, vehicle range, transient power requirements, response times, etc.). These engineering requirements of vehicle components, demanding even for conventional vehicles, are even more challenging in an environment utilizing fuel cells.

Furthermore, the increasing durability and longevity of conventional powertrains raises the bar for what consumers find acceptable in a contemporary vehicle. Today's passenger vehicles are being driven farther (approximately 26,000 additional miles per vehicle class), and surviving longer, than vehicles in the mid-1990s (NHTSA 2006). While niche users or early adopters may be willing to sacrifice certain performance attributes or vehicle amenities to be among the first to drive hydrogen fuel cell vehicles, widespread acceptance of this technology will demand that fuel cell vehicles be comparable to, or better than, contemporary vehicles in all major respects. Commercial success of fuel cell vehicles will necessitate that fuel cells and other vehicle components meet the continually increasing "comparable vehicle" baselines for durability, performance, and cost.

NO-REGRETS POTENTIAL

Even under the best case scenario of marked advancements in hydrogen and fuel cell technologies, it will be decades before fuel cell vehicles and hydrogen become cost-competitive with gasoline, diesel, and hybrid-electric vehicles (National Research Council 2004). Achieving broad market penetration will require a convergence of technical and logistical advancements on both the vehicle and the fueling infrastructure fronts. Given the enormity of these challenges, a concerted research effort in these areas requiring a considerable amount of time, energy, and funding will be critical.

A lack of success in any of these areas, however, could lead to a scenario in which hydrogen fuel cell vehicles do not become the predominant vehicle of tomorrow. Should that happen, other advanced vehicle designs facing far less daunting challenges may step in and go a long way toward serving similar objectives in reducing oil consumption, cutting GHG emissions, and improving local air quality. Even these vehicles, however, will require proper nurturing of research and development before becoming a practical alternative to today's petroleum-fueled internal combustion engine vehicles.

Fortunately, certain components of these contending alternative vehicle designs overlap with components necessary for the development of hydrogen fuel cell vehicles. Development of these elements is in some respects end-use neutral; dedicating funds toward their development does not require committing to one technology and abandoning others. Energy storage devices and power electronics, for example, will be essential not only to hydrogen vehicles, but to all electric-drive vehicles including PHEVs, HEVs, and EVs. As such, research into overlapping components with those vehicle designs stands to benefit not only hydrogen fuel cell vehicle research, but research into electric-drive vehicles as well.

By prioritizing research funding toward these "no-regrets" areas, one can support the evolution of vehicle technology without having to choose specific winners and losers.

Technologies *without* overlapping potential must, of course, also be pursued at various junctures, such as when they are deciding factors in whether a given powertrain or fuel type will succeed. Fuel cell vehicles, for example, will not progress without concerted research into improving the performance and durability of fuel cell stacks. While it is unlikely that stack research would be applicable to other transportation sector areas outside of fuel cell vehicles, the critical nature of the research makes it mandatory nonetheless.

That said, a number of current federal research areas focus upon technologies that are applicable on multiple fronts. Many electric-drive and power electronics components necessary for fuel cell vehicles, for example, are also key elements of contemporary or near-term vehicle designs like hybrid-electric and plug-in hybrid-electric vehicles. Advances in these near-term efficiency-improving technologies do not detract from hydrogen fuel cell vehicle R&D, but rather *advance* development of this longer-range vehicle research. The following section identifies a range of such technologies.

Energy Storage Devices

Energy and power requirements in fuel cell vehicles necessitate the use of large fuel cell stacks to meet performance specifications. However, by incorporating batteries into fuel cell vehicle designs, one can limit the performance burden placed on a fuel cell, accommodating reductions in both powertrain volume and system cost. The degree of fuel cell stack downsizing must be balanced against costs associated with increased energy storage requirements. In the near term, though, a “hybrid fuel cell vehicle” design has been shown to offer numerous cost-effective performance benefits over a fuel cell-only vehicle design (Markel et al. 2003).

Hybrid fuel cell vehicles can utilize batteries in a number of ways. Although vehicle designs can vary, batteries could be expected to provide electricity for motive power during the fuel cell’s startup period, provide supplemental boost power on demand during regular vehicle operation, and capture energy during regenerative braking activities. Furthermore, batteries could supply “smoothing” energy to the electric motor to overcome the limited transient response of fuel cells, as well as supply electricity to auxiliary loads. Given the many uses of stored energy and the relative costs of batteries versus fuel cells at this time, it is reasonable to expect that batteries or other energy storage devices will play an important role in upcoming fuel cell vehicle designs.

In addition to their role in fuel cell vehicles, batteries will play a critical role in a broad range of alternative vehicle designs, including EVs, HEVs, PHEVs, and 42-volt systems. It is worth noting that the use and battery specifications will differ for each of these designs. For example, electric vehicles require large batteries (on the order of 30 kWh) capable of providing a sustained level of energy for long periods of time in order to give the vehicle sufficient driving range. Today’s hybrid-electric vehicles, on the other hand, utilize their batteries much differently. They require batteries capable of providing short periods of boost power to an electric motor that supplements a modestly sized internal combustion engine. Providing a significant range of all-electric operation is not a design feature of HEVs, and thus their batteries hold much less energy than battery packs found in EVs. Today’s HEV battery packs are typically around 1–2 kWh.

Plug-in hybrid-electric vehicles effectively seek to bridge the gap between these two designs, with a battery capable of providing a substantial range of electric-only operation (e.g., between 10 and 40 miles), yet not requiring such a costly, large battery pack as found in EVs. The size of batteries in PHEVs will depend on their all-electric range. A PHEV 20 (yielding 20 miles of electric-only range) may require as little as 6–8 kWh and as much as 10–15 kWh, depending on battery life and durability (Kliesch and Langer 2006). Because battery life is shortened when used for deep cycling (running the battery from a near-full state of charge to near-empty), oversized batteries that use a smaller portion of their state of charge typically will offer longer life than smaller batteries used for deep cycling. Given the high cost of batteries today, these design considerations can significantly affect the economic viability of these vehicles.

According to the U.S. Department of Energy, the major challenges facing battery technology today can be grouped into five major categories (DOE 2006d):

- Cost
- Performance
- Life
- Abuse Tolerance
- Weight/Volume/Thermal Control

Although all five of these barriers are critical to the development of advanced vehicle batteries, cost is the dominant factor. Component costs will depend on the type of the battery, as design objectives for high-energy batteries differ from those of high-power batteries. Cost issues are universal, however. Objectives for overcoming these barriers are to identify key cost components (e.g., anodes, cathodes, electrolytes, separators), develop and test lower-cost versions of the components as well as packaging and production techniques, and work with potential suppliers to implement the changes (DOE 2006d).

At this time, two of the most prominent battery chemistries utilized in electric and hybrid-electric vehicles are nickel-metal hydride (NiMH) and lithium-ion (Li-ion) designs. Nickel-metal hydride batteries are used in today’s HEVs, as well as a number of recent EV models. Their in-use performance has shown better-than-expected longevity and durability, particularly in HEVs. While economies of scale could help reduce NiMH battery costs, a substantial increase in the price of nickel over the past few years will likely buoy the cost of batteries using this chemistry for some time.

Compared to NiMH, Li-ion batteries are smaller, lighter, and offer excellent energy density, making them particularly suitable for applications such as plug-in hybrid-electric vehicles. Although the performance characteristics of Li-ion batteries have improved in recent years, the technology is still prohibitively expensive, and further research in the areas of safety, durability, and calendar life is necessary (DOE 2006a). Despite these challenges, automakers have announced that Li-ion batteries will enter the HEV market (including Toyota’s Prius) within the next few years (Merx 2007; Rowley 2007).

Ultracapacitors are another type of energy storage device with potential vehicle applications. Unlike batteries, which store electrical charge chemically, ultracapacitors store their charge electrostatically. They are capable of withstanding hundreds of thousands of charges and discharges without product degradation, though for a given volume the amount of energy they store is smaller than the amount stored by a typical battery (NREL 2006). Given their performance characteristics, ultracapacitors are most applicable to uses requiring short bursts of power. As such, they could theoretically be used for modest power assist, or in conjunction with high-energy batteries as a pulse power source to meet both energy (supplied by the batteries) and power (supplied by the ultracapacitor) requirements. Designs using both batteries and ultracapacitors, however, would require additional power electronics for proper DC/DC conversion (NREL 2006).

The viability of ultracapacitors in hydrogen vehicles is currently being investigated. Ultracapacitors have been implemented in at least one demonstration fuel cell vehicle, Honda’s FCX. As for use as battery substitutes in electric and hybrid-electric vehicles, their applicability is less clear. At this time, ultracapacitors are capable of yielding only about half the energy density required by HEVs in power-assist mode (DOE 2006a). Furthermore, they are expensive. However, they do offer high power characteristics, which may, in time, make them suitable for 42-volt applications such as idle-off (in which sufficient power is provided to turn over a stopped engine, enabling fuel savings and emissions reduction at traffic lights, etc.). According to recent DOE analyses, an engine-off system utilizing a low-voltage ultracapacitor could improve midsize car fuel economy by 7–15 percent, while application of a high-voltage system in a mid-size power-assist HEV (with limited engine downsizing) could improve city fuel economy by more than 50 percent (DOE 2006a).

Power Electronics

Both fuel cell and hybrid-electric vehicles demand a high degree of electrical control. As such, a significant amount of overlap between these vehicle types exists in the area of electrical componentry, including control systems, inverters, converters, and electric motors. Collectively, these “power electronics” technologies offer a significant degree of no-regrets R&D potential. While many challenges remain in the area of power electronics — such as cost constraints; reliability, durability, and efficiency requirements; and size, weight, and mass-production requirements — R&D efforts aimed at these challenges would benefit fuel cell and electric-drive vehicles alike.

Power electronics manage the timing and flow of power between electrical components, as well as provide the intermediate power conditioning necessary for the components to operate with one another. Such conditioning includes converting between direct and alternating currents, controlling voltage and current magnitudes, and altering AC signal frequencies. In hybrid and fuel cell vehicles, where sophisticated power control between numerous electronic subsystems is critical, power electronics play a crucial role in vehicle operability.

Key power electronics components include electric motors, motor controllers (which direct power to and from specified locations), DC-to-DC converters (which convert between high- and low-voltage buses used by, for example, fuel cells and auxiliary loads, respectively), and inverters (which convert direct current output from a battery or fuel cell into alternating current utilized by the electric motor, or vice versa).

As vehicle manufacturers' interest in electric motors increases, component efficiency, cost, and weight improvements will become increasingly valuable. Numerous technical challenges face the continued development of power electronics for hybrid-electric and fuel cell vehicles, including cost, size, weight, thermal management, and durability (DOE 2006d). While cost is the primary challenge facing power electronics development, it is exacerbated by the need to concurrently meet the remaining technical hurdles.

Cost challenges arise largely from materials and manufacturing processes associated with electric motors and power electronic components. Permanent magnet motors, which offer admirable performance characteristics, are expensive due to both the magnetic materials and manufacturing processes. Switched reluctance motors are less expensive, though they have limited performance capabilities. Induction motors, a common type of AC electric motor, are a mature technology not expected to see dramatic improvements. Research is currently underway on polymer bonded particulate magnets that are markedly less expensive than those in permanent magnet motors and that perform well at high operating temperatures. Still, electric motor cost, weight, and volume goals set by the FreedomCAR and Fuel Partnership are a continuing challenge (DOE 2004a).

Size and weight challenges raise not only vehicle packaging and structural integrity issues, but thermal management issues as well: high-density power electronics are frequently bulky and heavy, limiting heat dissipation which in turn affects device performance and durability. According to the National Renewable Energy Laboratory, power electronics devices and electric motors that meet FreedomCAR and Vehicle Technologies program size and weight requirements lack the durability to operate in severe conditions (high temperatures, humidity, dirt, etc.) for 150,000 miles (DOE 2006e). The goal of developing a compact, lightweight, and durable power electronics system will require incorporating state-of-the-art cooling techniques.

Some of the latest power electronics research and development is focusing on capacitors and integrated devices. Capacitors, one of the primary components in inverters, account for a significant amount of inverters' expense, weight, and size. However, the electrolytic aluminum capacitor, one of the most common capacitor types, has numerous drawbacks: it is large, has a relatively short lifetime, and is vulnerable to high temperatures. On these fronts, two other types, polymer film and ceramic capacitors, look to be promising alternatives. Polymer-film capacitors still face high-temperature obstacles, but do offer benefits over traditional capacitors in other barrier areas. Ceramic capacitors offer perhaps the best promise in terms of size reduction and high-temperature functionality, though cost and failure mode-related challenges remain. Research on improved scaling and manufacturing techniques continues for both capacitor types (DOE 2004a, 2006d).

Vehicle Electrification

Conventional vehicles contain a number of mechanically and hydraulically actuated devices (e.g., alternators, belt-driven air conditioner compressors, hydraulic power steering, camoperated cylinder valves, etc.) whose operation places a load on the engine, drawing down vehicle efficiency. Over a typical driving cycle, engine-driven accessories such as the alternator, water pump, oil pump, and power steering pump are responsible for 8–10 percent of a vehicle's energy consumption (NESCCAF 2004). In a number of cases, these devices use legacy designs that are either inefficient or underutilized, requiring constant energy despite periodic use. Electrification of these components offers a way to operate them with greater precision, minimize energy losses, preserve fuel, and reduce emissions.

Vehicle electrification is slowly being introduced into the market at this time, primarily in hybrid-electric vehicles. Drive-by-wire (electronic throttle control) and brake-by-wire designs open up new opportunities for engineers to mate driver demand with vehicle conditions to achieve optimal vehicle response in terms of efficiency, performance, and emissions reduction.

Intermittent-use loads are particularly amenable to vehicle electrification. Power steering pumps, for example, operate continuously in conventional vehicles, despite the fact that they see only periodic use. With vehicle electrification, the continual load drawn from the pump's operation can be replaced with on-demand electronic actuation.

Camless valve actuation is another example of the possibilities that arise through vehicle electrification. Using electromechanical solenoids, valves can be opened or closed at will, removing both the camshaft and mechanical valve actuation at the cylinder head. This design does not simply reduce frictional and pumping losses; by decoupling valve control from engine operation, cylinder combustion can be tailored for optimal performance while minimizing fuel consumption and emissions levels. Electromechanical camless valve systems are expected to yield a 5–10 percent improvement in fuel consumption over engines with variable valve lift and timing (VVLT) and 15 percent or more over fixed-timing engines (National Research Council 2002).

Air conditioning, which can draw as much as 6 kW peak power (but usually more in the range of 4 kW), accounts for a large portion of accessory energy use (Johnson 2002; DOE 2006d). According to the U.S. Department of Energy, nearly a half-million barrels of gasoline are used each day to cool light-duty passenger vehicle cabins (DOE 2006d). Although electrification of high-power accessories like A/C units has not significantly penetrated the market, potential applications exist under a 42-volt vehicle voltage architecture. Adoption of electric A/C compressors could improve vehicle efficiency in a few ways. First, by decoupling the A/C from the engine, the compressor speed can operate independent of engine speed, a critical factor for vehicles with idle-off capability. Second, by meeting cooling requirements through compressor speed variation (rather than displacement variation utilized in variable displacement compressor systems), it is possible to achieve volumetric efficiency gains, even despite the reduced efficiencies of electric drive relative to belt drive (NESCCAF 2004).

Although electrically controlled A/C will require a higher voltage architecture than the existing 14-volts, the continuing need for additional electrical power in vehicles suggests that such an architecture may become more prevalent in the coming years. Whereas today's vehicle electrical architecture offers only a few kW of excess power, limiting the degree of electrification, a 42-volt system would offer roughly four times as much excess power (NESCCAF 2004). This would allow for broader utilization of electrical components, including electrical accessories, electrical power steering, electrically controlled A/C, engine-off using an integrated starter-generator, and regenerative braking.

Research to improve the efficiency of these devices, and to incorporate them into fuel cell vehicle designs, will help minimize power requirements of a vehicle's fuel cell stack. Furthermore, many of these technologies are or will be applicable to hybrid-electric or 42-volt systems, making them suitable research areas with a variety of near- and far-term applications.

Supplemental Vehicle Areas

A number of other "supplemental" areas of vehicle research exist that, while not specifically related to hydrogen vehicle activities, would ease certain challenges facing the technology. Vehicle mass reduction and parasitic loss reduction, for example, would improve vehicle fuel economy, reducing power demands that are, in turn, tied to fuel cell stack requirements. The same improvements, however, are not drivetrain-specific and could equally well be applied to conventional vehicles. As such, they will receive only brief mention in this report.

Development of lightweight automotive materials that could be implemented on vehicles without compromising safety, performance, cost, or recyclability would be a boon not only to fuel cell vehicles, but to conventional vehicles as well. Lightweight materials offer a number of potential advantages, including weight reduction, design flexibility to accommodate vehicle packaging constraints, and consolidation of components to ease assembly requirements. Developments in plastics, steel, and carbon fiber composites have shown that dramatic weight reductions are possible with their use. As high-priced fuel spurs greater interest in fuel-efficient models, certain applications of lightweight materials may become more prevalent. The FreedomCAR and Vehicle Technologies program has set a materials technology performance goal for 2012 to cost-effectively reduce passenger vehicle body and chassis weight by 50 percent while maintaining the performance, safety, and recyclability of a model year 2002 vehicle (DOE 2006d).

Materials and manufacturing-related costs, however, are still a significant hurdle, limiting applicability on a mass-market basis. Challenges include high-volume production methods, joining technologies (for mating lightweight and non-lightweight materials), and technologies to aid in recycling and repair of lightweight materials (DOE 2006d). The high cost-related barriers prompted the National Research Council to suggest that DOE move a portion of its materials research funding to areas with greater potential for success (National Research Council 2005).

Another broad area of research applicable to fuel cell, hybrid-electric, and conventional vehicles alike is that of parasitic loss reduction. These losses include wind resistance, rolling resistance, powertrain friction, and auxiliary loads such as air conditioning. Research efforts to minimize parasitic losses in vehicles would have widespread applicability, as they are universal challenges to all passenger vehicles.

Cellulosic Ethanol

Pursuing cellulosic ethanol production does not have significant crossover potential in terms of hydrogen fuel cell vehicle development. However, cellulosic ethanol is not as daunting an endeavor as hydrogen, and it does have certain tangential benefits with respect to the existing vehicle paradigm. Today's ethanol market is already straining to meet demand for E85 and gasoline additives. In order to greatly expand the number of vehicles running on ethanol without placing excessive demand on corn production, a dramatic increase in vehicle efficiency will be required. Making such improvements to conventional vehicle efficiency would ease U.S. oil consumption regardless of ethanol use. In time, as cellulosic ethanol production grows, incorporation of the alternative fuel would further reduce the petroleum demands of conventional and other efficient vehicle technologies (such as PHEVs).[7]

In terms of overlap with hydrogen, biomass could theoretically be used as a feedstock source for the production of hydrogen. However, costs, including capital equipment, feedstock, distribution, and fixed costs, would also need to be reduced (National Research Council 2004). As such, it appears unlikely that biofuels will play a role in the development of a hydrogen infrastructure, though a breakthrough technological development could change that outlook. According to the U.S. Department of Energy, a conceivable, albeit remote, use of biofuels would be to leverage their liquid state for use as a distribution tool in a hydrogen network. This conceptual idea involves mass-producing biofuels at facilities located near feedstocks, taking advantage of economies of scale. The biofuels would then be distributed in liquid form with relative ease (compared to the numerous distribution challenges facing hydrogen) to distributed reforming sites where they would, in turn, be converted into hydrogen in a process similar to steam reformation (DOE 2006b). Short of dramatic breakthroughs in conversion efficiencies and biofuel distribution challenges, however, such a scenario seems unlikely.

It bears mentioning that despite a lack of obvious overlap between cellulosic ethanol and longer-term hydrogen fuel cell vehicle research, biofuels independently offer many of the same benefits as hydrogen, including reduced oil dependence, in-use emissions reduction, and GHG emissions reduction. The fact that vehicle hardware issues for flex-fuel[8] or other ethanol-consuming vehicle designs (such as a knock-suppressing engine) are modest compared to fuel cell vehicles suggests that further research into biofuels is well warranted. At the same time, it should be reiterated that increasing corn ethanol production capacity — especially for use in vehicles with today's fuel efficiencies — would serve far less good than applying those resources to cellulosic ethanol development. The poorer characteristics of corn ethanol relative to cellulosic suggest that corn ethanol should largely be viewed as a stepping stone to a coming cellulosic market.

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[7] While a number of hurdles would be need to be overcome before a PHEV operating primarily on electricity and cellulosic ethanol could be widely adopted in the market, the significant oil savings potential of such a design warrants the pursuit of research facilitating that option.

[8] Flex-fuel vehicles require relatively low-tech substitutions, such as the addition of a fuel sensor and replacement of a modest number of components to make the vehicle alcohol-tolerant.

Carbon Capture and Sequestration

As noted earlier in this report, two of the most prominent methods for producing hydrogen are steam reformation and electrolysis. In steam reformation, hydrocarbons (such as natural gas) are heated in a combustion chamber, and a catalyst is used to break the fuel into separate components, including hydrogen. Electrolysis, on the other hand, uses electricity to break water molecules into hydrogen and oxygen molecules. While electrolysis could be performed using carbon-free nuclear or renewable energy (either grid-based or grid-free, in the case of, for example, a hydrogen-producing wind farm), it could also be performed using carbon-intensive sources such as coal-generated electricity.

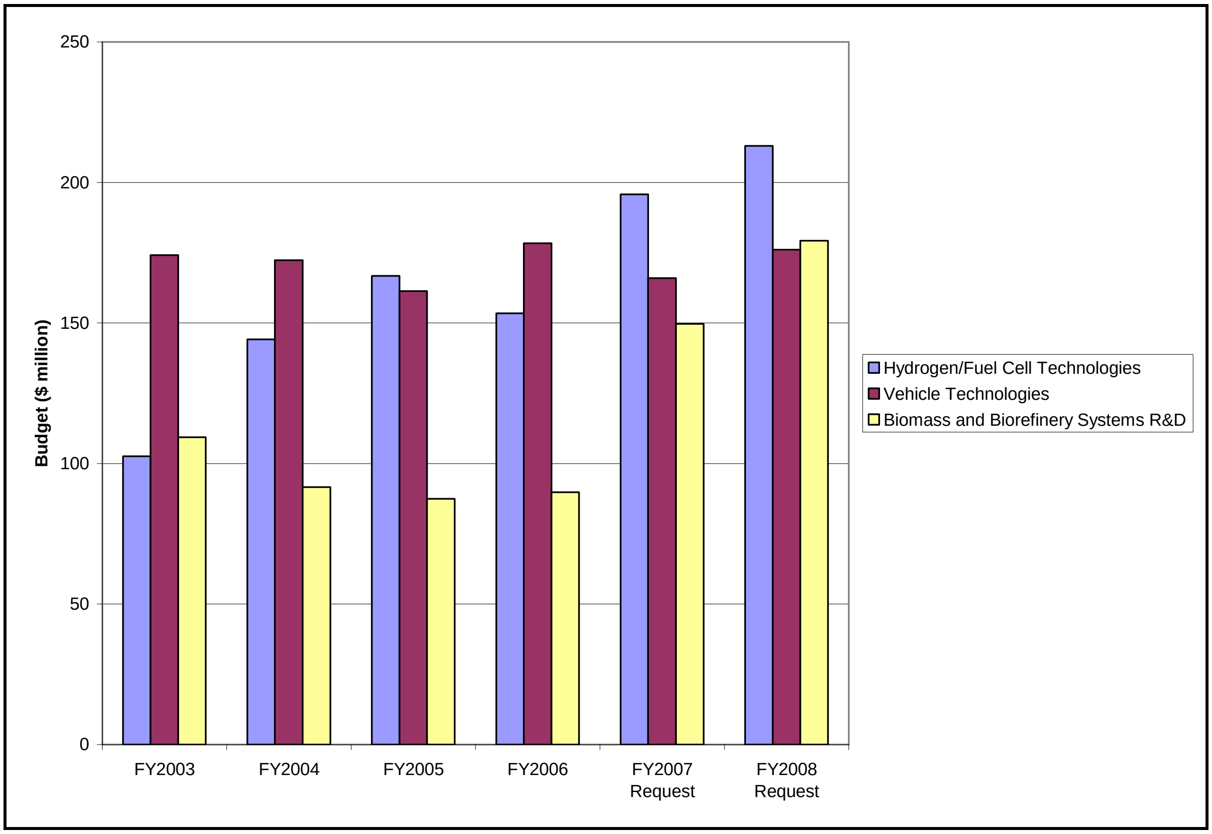
Today, the vast majority (approximately 96 percent) of hydrogen produced globally uses a fossil fuel feedstock. Experts predict it is “highly likely that fossil fuels will be the principal sources of hydrogen for several decades” (National Research Council 2004). Given that, in order to insure that the growth of a hydrogen economy does not accelerate climate change, committed research in the area of carbon capture and sequestration of CO_2 emissions in geologic or oceanic reservoirs is essential.

Challenges facing carbon capture and sequestration, both technical and logistical (such as property rights, liability, and public acceptance issues) are, without question, daunting. It is yet to be a proven solution to climate change challenges and may encounter further feasibility challenges in the coming years. Still, the potential of such an approach suggests that research in this area should continue. It is important to note that the value of this research is not contingent upon the success of a transition to hydrogen. Even with uncertainty about the long-term viability of a hydrogen economy, implementation of carbon capture and sequestration would radically alter the carbon profile of electricity generation (a major success in its own right) and — should grid-based electrification of vehicles, such as plug-in hybrids, expand — the transportation sector as well.

ADVANCED VEHICLE TECHNOLOGY FUNDING

Examination of federal R&D funding levels for various vehicle technologies offers insight into the administration’s perspective on relative technology potential, as well as into politically popular research areas. The following figure and tables detail program- and subprogram-level funding trends within the Department of Energy’s EERE Vehicle Technologies, Biomass and Biorefinery Systems R&D, and Hydrogen Technology programs, which cover many of the technologies noted in this report. The tables document technology funding patterns for Fiscal Years 2002 through 2006, along with the FY 2007 and FY 2008 administration requests.

Figure 2. EERE Budget for Hydrogen/Fuel Cell Technologies, Vehicle Technologies, and Biomass/Biorefinery Systems R&D, FY 2003-2008



Although funding for certain R&D areas has dramatically increased in recent years, it should be noted that funding, per se, does not guarantee program success. In order to ensure that the policy objectives of investments are met, it is essential to have an effective policy framework to accompany technology investment. Without such a framework, investments of public monies could largely be squandered.

Vehicle Technologies

A number of the technologies noted in this report as having no-regrets potential fall under the Vehicle Technologies program. In particular, the Hybrid and Electric Propulsion subprogram encompasses many of these areas, including energy storage devices, power electronics, and electric motors. As shown in Table 1, funding for Hybrid & Electric Propulsion remained relatively constant between Fiscal Years 2003 and 2006, with an 18 percent increase in the FY 2007 request.[9] A new budget structure in FY 2008 complicates tracking, but the new Hybrid Electric Systems subprogram (which includes the Vehicle Systems and Hybrid & Electric Propulsion subprograms, as well as the Testing & Evaluation activity previously in the Technology Introduction subprogram) may see, pending approval, a

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[9] The FY 2007 Operating Plan increased Vehicle Technologies Program funding by an additional $22 million over the request.

net increase of roughly $13 million over 2007 request levels, to a total of $80.7 million. Justification of this increase lies in part upon hybrid system development, notably development of plug-in hybrid-electric vehicles.

Table 1. Department of Energy Program Budget, Vehicle Technologies Program (millions of dollars)

	FY2002	FY2003	FY2004	FY2005	FY2006	FY2007 Request	FY2008 Request
Hybrid Electric Systems	–-	–-	–-	–-	–-	–-	$80.7
Vehicle Systems	$14.9	$13.5	$13.9	$13.0	$12.7	$13.3	–-
Hybrid & Electric Propulsion	$47.1	$42.0	$43.4	$44.1	$42.8	$50.8	–-
Advanced Combustion Engine R&D	$47.2	$55.3	$52.7	$48.5	$40.6	$46.7	$34.6
Materials Technologies	$39.2	$36.1	$38.6	$36.0	$34.4	$29.8	$33.4
Fuels Technologies	$24.7	$19.2	$15.9	$12.4	$13.4	$13.8	$13.8
Technology Integration	–-	–-	–-	–-	–-	–-	$13.7
Innovative Concepts	$0.6	$1.6	$0.5	$0.5	$0.5	$0.5	–-
Technology Introduction	$3.5	$4.6	$4.8	$4.9	$6.3	$11.0	–-
Biennial Peer Reviews	–-	–-	$0.5	–-	$1.0	–-	–-
Technical/Program Management Support	$2.4	$2.0	$2.1	$1.9	$2.5	–-	–-
Congressionally Directed Activities	n/a	n/a	n/a	–-	$24.3	–-	–-
SUBTOTAL	$179.4	$174.2	$172.4	$161.3	$178.4	$166.0 [a]	$176.1

Notes:

[a] FY 2007 Operating Plan was raised to $188.0 million (DOE 2007b). Subprogram-level allocations were unavailable.

Sources: FY 2006–2008: DOE 2007c; FY 2005: DOE 2006c; FY 2004: DOE 2005b; FY 2003: DOE 2004b; FY 2002: DOE 2003.

n/a: Not available.

As much of the success of plug-in hybrids will hinge upon progress in advanced batteries, some of the key Hybrid Electric Systems subprogram objectives are to cut the production cost of high-power (25 kW) batteries from $3,000 in 1998 to $500 in 2010 to enable cost-competitive hybrid vehicles; to cut the production cost of high-energy and high-power batteries from $1,000/kWh in 2006 to $300/kWh in 2014 to enable cost-competitive PHEVs; and to accelerate development of low-cost electric motors and controls sufficient to meet the performance requirements of plug-in hybrid-electric vehicles (DOE 2006d, 2007a). The importance of advancements in energy storage technologies is recognized to some degree in the 2007 budget, with a 68 percent ($16.6 million) increase in allocated program dollars (see Table 2, with historical trends in Table 3). Still, these numbers level off in FY 2008 and moreover, pale in comparison to funding increases for biomass/biorefinery and hydrogen technology research, specified in Tables 4 and 5 respectively.

Table 2. Department of Energy Activity Budget, Energy Storage R&D (millions of dollars)

	FY 2006			FY 2007			FY 2008		
	HEV	PHEV	Total	HEV	PHEV	Total	HEV	PHEV	Total
Energy Storage R&D	$23.1	$1.4	$24.5	$23.5	$17.6	$41.1	$23.6	$18.2	$41.8

Source: Wall (2007)

Table 3. Department of Energy Program Budget, Hybrid & Electric Propulsion/ Hybrid Electric Systems Subprogram (millions of dollars)

	FY2002	FY2003	FY2004	FY2005	FY2006	FY2007 Request	FY2008 Request [b]
Energy Storage	$24.1	$21.6	$22.3	$22.5	$24.5	$31.1 [a]	N/A
High Power Energy Storage	$17.3	$17.2	$16.5	$16.9	$16.8	$17.2	N/A
Advanced Battery Dvlpmt.	$4.4	$2.4	$1.4	$1.5	$1.4	$7.6	N/A
Exploratory Tech. Research	$2.4	$1.9	$4.4	$4.1	$6.3	$6.3	N/A
Advanced Power Electronics	$14.2	$13.4	$13.2	$12.8	$12.9	$13.7	N/A
Subsystem Integration and Development	$8.8	$7.1	$7.9	$8.7	$5.4	$4.6	N/A
Light Vehicle Propulsion and Anc. Syst.	$3.9	$3.1	$3.0	$3.5	$3.6	$4.6	N/A
Heavy Vehicle Propulsion and Anc. Syst.	$4.9	$3.9	$4.9	$5.2	$1.8	—	N/A
Vehicle & Systems Simulation and Testing	N/A	N/A	N/A	N/A	N/A	N/A	$21.1
Energy Storage R&D	N/A	N/A	N/A	N/A	N/A	N/A	$41.8
Advanced Power Electronics and Elec. Motors R&D	N/A	N/A	N/A	N/A	N/A	N/A	$15.6
SBIR/STTR	—	—	—	—	—	$1.4	$2.1
SUBTOTAL	$47.1	$42.0	$43.4	$44.1	$42.8	$50.8	$80.7

Notes:

[a] Note, this column reflects the FY 2007 administrative request only; subsequent increases in the FY 2007 Operating Plan are not included here and therefore differ from numbers shown in Table 2

[b] The Hybrid Electric Systems subprogram reflects a new budget structure for FY 2008. It incorporates two former subprograms, Vehicle Systems and Hybrid & Electric Propulsion, as well as the Testing and Evaluation activity previously within the Technology Introduction subprogram.

Sources: FY 2006–2008: DOE 2007c; FY 2005: DOE 2006c; FY 2004: DOE 2005b; FY 2003: DOE 2004b; FY 2002: DOE 2003

N/A: Not applicable.

The Administration's detailed justification for the FY 2008 Energy Storage R&D budget identifies the activity's major related challenges as "developing batteries that are rugged, long-lasting, affordable, lighter, [that] hold a substantial charge, and [that] work in all climates and seasons" (DOE 2007c). While these are not inaccurate assessments, research into the safety of advanced (such as lithium-ion) batteries should see equal attention. Recent fires caused by lithium-ion batteries have yielded a number of recalls in the laptop computer industry; the potential consequences of a battery-induced fire in an electric or hybrid-electric vehicle would be a threat not only to the vehicle's occupants, but to the ultimate success of electric-drive vehicles in general. Such safety research should address, at a minimum, manufacturing flaws, crash protection, and overcharge protection.

Funding levels have increased for many of the technology areas noted in this report, though in numerous cases funding increases have come at the expense of other Energy Efficiency and Renewable Energy (EERE) program areas, such as heavy vehicle research. Research in heavy vehicle propulsion and ancillary systems (reduction of $1.8 million), heavy vehicle high-strength weight-reduction materials (reduction of $2.7 million), and heavy vehicle systems R&D (reduction of $2.6 million), for example, all saw significant proposed cutbacks for FY 2007. While a detailed assessment of heavy vehicle research is outside the scope of this report, heavy vehicles' potential as a source for reducing petroleum demand in the United States should not be underestimated.

Biomass and Biorefinery Systems R&D

Biomass- and biorefinery-related R&D, which has seen a near-constant level of funding for the past five years, saw a dramatic increase in FY 2007 from roughly $90 million to just shy of $200 million, as shown in Table 4.

Table 4. Department of Energy Program Budget, Biomass and Biorefinery Systems R&D Program[a] (millions of dollars)

	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007 Request	FY 2008 Request
Feedstock Infrastructure	[b]	$1.9	$1.0	$2.0	$0.5	$10.0	$10.0
Platforms Research and Development	[b]	$27.9	$28.9	$29.3	$19.5	$50.5	$59.4
Utilization of Platform Outputs R&D	[b]	$37.8	$20.1	$20.5	$22.9	$89.2	$104.9
Industrial Gasification	[b]	$14.3	—	—	—	—	—
Cellulosic Ethanol Reverse Auction	[b]	—	—	—	—	—	$5.0
Congressionally Directed Activities	[b]	$26.6	$41.2	$35.3	$46.8	—	—
Technical/Program Management Support	[b]	$0.8	$0.4	$0.4	—	—	—
SUBTOTAL	$112.5	$109.3	$91.6	$87.5	$89.8	$149.7[c]	$179.3

Notes:

[a] Includes both Energy Supply and Energy Conservation appropriations.

[b] Research categories for FY 2002 data only include Advanced Biomass Technology R&D ($38.4M ES + $7.1M EC), Systems Integration and Production ($49.3M ES + $17.1M EC), and Technical Program Management Support ($0.5M EC).

[c] FY 2007 Operating Plan was raised to $199.7 million (DOE 2007b). Subprogram-level allocations were unavailable.

Sources: FY 2006–2008: DOE 2007c; FY 2005: DOE 2006c; FY 2004: DOE 2005b; FY 2003: DOE 2004b; FY 2002: DOE 2003.

Although the energy and GHG benefits of cellulosic ethanol development warrant additional funding in this area, the disparity between biomass-related funding and that of vehicle technologies with greater near-term potential raises questions. Given the importance of the entire suite of technologies noted in this report, aggressive R&D budgeting on *all* levels should be pursued.

Hydrogen Technology

Funding for hydrogen and fuel cell R&D has steadily climbed throughout the decade. As shown in Table 5, funding for the Hydrogen Technology program nearly doubled between 2003 and 2007, with FY 2008 requests climbing even higher to $213 million. The result this year — nearly $60 million over the FY 2006 budget — will benefit numerous areas of hydrogen and fuel cell research and development.[10] However, funding levels are disproportionately large compared to other program areas with more promising near-term potential.

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[10] It remains to be seen to what level Congressionally directed funds get reinstated. Minimizing these earmarks will, as the National Research Council suggests, better allow researchers to meet FreedomCAR and Fuel Partnership program milestones and targets (National Research Council 2005).

Table 5. Department of Energy Program Budget, Hydrogen Technology Program (millions of dollars)

	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007 Request	FY 2008 Request
Hydrogen Production and Delivery R&D	$11.1	$11.2	$10.1	$13.3	$8.4	$36.8	$40.0
Hydrogen Storage R&D	$6.1	$10.8	$13.2	$22.4	$26.0	$34.6	$43.9
Safety, Codes & Standards	$4.5	$4.5	$5.6	$5.8	$4.6	$13.8	$16.0
Education	$1.4	$1.9	$2.4	—	$0.5	$2.0	$3.9
Systems Analysis	incl. above	incl. above	$1.4	$3.2	$4.8	$9.9	$11.5
Transportation Fuel Cell Systems	$7.5	$6.2	$7.3	$7.3	$1.1	$7.5	$8.0
Distributed Energy Fuel Cell Systems	$5.5	$7.3	$7.2	$6.8	$0.9	$7.4	$7.7
Fuel Processor R&D	$20.9	$23.5	$14.4	$9.5	$0.6	$4.1	$3.0
Fuel Cell Stack Component R&D	$12.6	$14.8	$24.6	$31.7	$30.7	$38.1	$44.0
Technology & Infrastructure Validation	$5.7	$11.5	$15.6	$26.1	$33.3	$39.6	$30.0
Technology Validation	—	$1.8	$9.8	$17.8	n/a	n/a	n/a
Infrastructure Validation	$5.7	$9.7	$5.8	$9.5	n/a	n/a	n/a
Manufacturing R&D	—	—	—	—	—	$2.0	$5.0
Congressionally Directed Activities	n/a	$10.6	$42.0	$40.2	$42.5	—	—
Technical and Program Support	$0.2	$0.4	$0.4	$0.5	—	—	—
SUBTOTAL	$75.6 [a]	$102.6	$144.2	$166.8	$153.5	$195.8 [b]	$213.0

Notes:

[a] Does not include Congressionally directed activities.

[b] FY 2007 Operating Plan was lowered slightly from the FY 2007 request to $193.6 million (DOE 2007b). Subprogram-level allocations were unavailable.

Sources: FY 2006–2008: DOE 2007c; FY 2005: DOE 2006c; FY 2004: DOE 2005b; FY 2003: DOE 2004b; FY 2002: DOE 2003

Funding for Energy Storage R&D, for example, saw a $17.3 million increase in the same time frame (FY 2006 to FY 2008), to a sum total of $41.8 million. Given the critical relationship between energy storage breakthroughs and the success of an electric-drive vehicle market that could significantly reduce oil consumption, in-use emissions, and (depending on electricity generation fuel mix) GHG emissions in a time frame much nearer than fuel cell vehicles, a greater focus on advanced battery research is warranted.

CONCLUSIONS

Advanced vehicle technologies have the potential to ease many of the environmental and political challenges associated with U.S. petroleum demand. Extracting the United States from dependence on Middle Eastern oil, mitigating the sources of climate change, and improving regional air quality are a few of the major objectives that could be served through greater use of alternative vehicle technologies. Vehicle electrification in the form of plug-in hybrids or electric vehicles, alternative fuel vehicles running on cellulosic ethanol, and hydrogen-powered fuel cell vehicles all offer alternative pathways toward reducing petroleum consumption in the transportation sector.

Penetrating the vehicle market with any of these technologies, however, will be neither easy nor inexpensive. To that end, over the past fifteen years, a number of government-industry partnerships were formed to set benchmarks and technical goals, and to develop agendas aimed at reducing technology costs and minimizing market barriers. The PNGV program and subsequent FreedomCAR and Fuel Partnership, and more recently the Advanced Energy Initiative and “20-in-10” plan, are a few of the prominent programs and agendas supporting research and development of advanced vehicle technologies. Both federal funding for these technologies and public interest in them have increased in recent years.

Enthusiasm for individual technologies has waxed and waned over the years, as breakthroughs and setbacks have come to pass. At this time, both electricity (especially for use in plug-in hybrid-electric vehicles) and biofuels are being viewed as promising alternatives with near-term potential. While neither of these technologies is without challenges, they face fewer hurdles than hydrogen fuel cell vehicles, long envisioned as the “holy grail” of advanced vehicle technologies. Important advances have been made over the past few years addressing hydrogen and fuel cell vehicle barriers, in large part because of the committed research efforts and continued federal funding in those areas. Yet there is still a long way to go. Fuel cells must overcome a broad set of economic, technical, and market barriers before becoming a practical alternative to today’s petroleum-fueled internal combustion engine.

The possible advantages of a transportation sector utilizing hydrogen are well documented, though the benefits of such a system will be highly dependent upon hydrogen feedstock source and fuel infrastructure development choices. Numerous pathways exist by which a hydrogen-based transportation system could arrive; the various methods of fuel production, modes of distribution, and infrastructure configurations — as well as designs of hydrogen vehicles themselves — offer up a broad range of scenarios in which a hydrogen economy could evolve. Some of these scenarios are ideal, meeting both clean energy and clean vehicle profiles. Others could be moderately favorable to oil independence and/or environmental concerns, while some scenarios would offer little benefit over competing contemporary technologies. Considering the multi-dimensional challenges facing hydrogen and fuel cell vehicle development, significant market penetration of hydrogen vehicles is decades away, even under the most promising technology development scenario.

Given the enormity of these challenges, a rigorous hydrogen R&D effort entailing considerable amounts of time, energy, and funding is critical. Fortunately, many of the research areas related to hydrogen fuel cell vehicles overlap with technologies that can be applied to other, more near-term advanced vehicle technologies. These R&D areas are good investment candidates because they not only support the long-term goal of advancing hydrogen fuel cell vehicle research, but also have nearer-term applications that justify the research, even if a hydrogen vehicle infrastructure were not to pan out. Energy storage devices (such as advanced batteries and ultracapacitors), power electronics, vehicle electrification, lightweight materials, and parasitic loss reduction all offer significant potential in this capacity. These components can be utilized in a number of promising energy-saving advanced vehicle designs, including hybrid-electric vehicles, plug-in hybrids, and possibly (depending on the success of battery R&D) electric vehicles as well.

Advances in carbon capture and sequestration research have similar potential in that regardless of the status of hydrogen development, successful capture and sequestration efforts could offer CO_2 reductions from electric power plants. Should grid-based electric or hybrid-electric vehicles see market penetration, such benefits would shift into the transportation sector as well. Even cellulosic ethanol, while having little direct bearing on hydrogen research, has possible indirect benefits in that addressing cellulosic ethanol cost and supply issues will necessitate improving vehicle efficiency.

Governmental entities allocating limited funds for research, development, and demonstration projects can make their investments go further by prioritizing the technologies that simultaneously build a path toward commercialization of fuel cell vehicles *and* increase the viability of hybrid-electric or other vehicle technologies emerging today. Advances in these technologies, which can boost efficiencies in near-term vehicles, do not detract from long-term transportation energy objectives; rather, they advance such objectives even further. These investments have improved chances of helping achieve environmental and oil savings goals regardless of when or whether hydrogen fuel cells emerge as a winning vehicle technology.

Oil consumption-related challenges facing this country’s transportation sector are simply too great to ignore in the hope that a transition to hydrogen will ease these matters. Uncertainties persist with hydrogen and, moreover, even a successful transition to it will be decades away at the earliest. By focusing on a no-regrets approach to research and development, we can attain the benefits of bringing clean and efficient nearer-term vehicle technologies to market, while simultaneously pursuing our longer-term sustainable transportation goals.

REFERENCES

ACEEE (American Council for an Energy-Efficient Economy). 2007. "President Short-Sells the First Fuel in the Race for Energy Security." http://www.aceee.org/press/0701sotu.htm. January 24.

Bond, K., C. Levin, D. Stabenow, and G. Voinovich. 2005. *Amendment 925 to S 10 (Senate Energy Bill).* June 23.

Davis, S.C. and S.W. Diegel. 2007. *Transportation Energy Data Book: Edition 26.* ORNL-6978. Oak Ridge, Tenn.: Oak Ridge National Laboratory, Center for Transportation Analysis.

DOE (U.S. Department of Energy). 2003. *Department of Energy FY 2004 Congressional Budget Request.* Washington, D.C.: U.S. Department of Energy.

———. 2004a. *FreedomCAR and Vehicle Technologies: Multi-Year Program Plan.* Washington, D.C.: U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies.

———. 2004b. *Department of Energy FY 2005 Congressional Budget Request.* Washington, D.C.: U.S. Department of Energy.

———. *2005a. Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan.* Washington, D.C.: U.S. Department of Energy.

———. 2005b. *Department of Energy FY 2006 Congressional Budget Request.* Washington, D.C.: U.S. Department of Energy.

———. 2006a. *FY 2005 Progress Report for Energy Storage Research and Development.* Washington, D.C.: U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies.

———. 2006b. *Renewable Liquid Fuels Reforming.* www.eere.energy.gov/hydrogenandfuelcells/production/liquid_fuels.html. Washington, D.C.: U.S. Department of Energy.

———. 2006c. *Department of Energy FY 2007 Congressional Budget Request.* Washington, D.C.: U.S. Department of Energy.

———. 2006d. *FreedomCAR and Vehicle Technologies Program: Multi-Year Program Plan.* Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, FreedomCAR and Vehicle Technologies Program.

———. 2006e. *FreedomCAR and Fuel Partnership: Electrical and Electronics Technical Team*

Roadmap.http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap.pdf. Washington, D.C.: U.S. Department of Energy.

———. 2007a. *Plug-In Hybrid Electric Vehicle R&D Plan. External Draft.* Washington, D.C.: U.S. Department of Energy. February.

———. 2007b. *Department of Energy FY 2007 Operating Plan by Appropriation.* Washington, D.C.: U.S. Department of Energy. March 16.

———. 2007c. *Department of Energy FY 2008 Congressional Budget Request.* Washington, D.C.: U.S. Department of Energy.

EIA (Energy Information Administration). 2006a. *Emissions of Greenhouse Gases in the United States, 2005.* Table 6, Table 10, and annual. Washington, D.C.: U.S. Department of Energy. November.

———. 2006b. *Annual Energy Outlook 2006.* Reference Case Table A7. Washington, D.C.: U.S. Department of Energy, Office of Integrated Analysis and Forecasting.

———. 2007a. *Annual Energy Outlook 2007.* Reference Case Table A7. Washington, D.C.: U.S. Department of Energy, Office of Integrated Analysis and Forecasting.

———. 2007b. *International Energy Outlook 2007.* Tables A10 and A11. Washington, D.C.: U.S. Department of Energy.

EPA (U.S. Environmental Protection Agency). 2005. National Emission Inventory Air Pollutant Emission Trends website. www.epa.gov/ttn/chief/trends.

———. 2006. *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 through 2006.* EPA420-R-06-011. Washington, D.C.: U.S. Environmental Protection Agency.

Greene D. and S. Ahmad. 2005. *Costs of U.S. Oil Dependence: 2005 Update.* ORNL/TM-2005/45. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Greene, N. 2004. *Growing Energy: How Biofuels Can Help End America's Oil Dependence.* New York, N.Y.: Natural Resources Defense Council.

Jennings, B. 2005. "The U.S. Ethanol Industry: Exceeding Expectations." http://www.state.sd.us/puc/pucevents/Energy%20Conf%20Presentations/Brian%20Jennings-%20US%20Ethanol%20Industry.pdf. Presented at the South Dakota Public Utilities Commission Energy Conference, April 20.

Johnson, V.H. 2002. *Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach.* SAE Paper No. 2002-01-1957. Warrendale, Penn.: Society of Automotive Engineers.

Karagianis, L. 2007. “Ethanol Magic.” MIT Spectrum. Vol. XVIII, No. VIII. http://web.mit.edu/giving/spectrum/winter07/powering-up/ethanol.html.

Kliesch, J. and T. Langer. 2006. *Plug-In Hybrids: An Environmental and Economic Performance Outlook.* Washington, D.C.: American Council for an Energy-Efficient Economy.

Markel, T. and A. Simpson. 2006. “Plug-In Hybrid Electric Vehicle Energy Storage System Design.” In *Proceedings of the 2006 Advanced Automotive Battery and Ultracapacitor Conference*. Oregon House, Calif.: Advanced Automotive Batteries.

Markel, T., M. Zolot, K.P. Wipke, and A.A. Pesaran. 2003. *Energy Storage System Requirements for Hybrid Fuel Cell Vehicles.* http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/aabc03_nrel_esfc_vr3.pdf. Golden, Colo.: National Renewable Energy Laboratory.

Merx, K. 2007. “GM Shows Inner Workings of Hybrid Battery Research Lab.” http://www.freep.com/apps/pbcs.dll/article?AID=/20070313/BUSINESS01/703130311/1014. *Detroit Free Press*, March 13.

Moran, S. 2006. “Biofuels Come of Age as the Demand Rises.” *New York Times*, September 12.

National Research Council. 2002. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards.* Washington, D.C.: National Academy Press.

———. 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* Washington, D.C.: National Academy Press.

———. 2005. *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report.* Washington, D.C.: National Academy Press.

NCGA (National Corn Growers Association). 2006. *How Much Ethanol Can Come From Corn?* Version 11-9-06. http://www.ncga.com/ethanol/pdfs/2006/HowMuchEthanolCan%20ComeFromCorn.v.2.pdf. Chesterfield, Mo. and Washington, D.C.: National Corn Growers Association.

NESCCAF (Northeast States Center for a Clean Air Future). 2004. *Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles.* Boston, Mass.: Northeast States Center for a Clean Air Future

NHTSA (National Highway Traffic Safety Administration). 2006. *Vehicle Survivability and Travel Mileage Schedules*. National Center for Statistics and Analysis. DOT HS 809 952. January.

NREL (National Renewable Energy Laboratory). 2006. *Energy Storage – Ultracapacitors.* http://www.nrel.gov/vehiclesandfuels/energystorage/ultracapacitors.html. Golden, Colo.: National Renewable Energy Laboratory.

RFA (Renewable Fuels Association). 2006. *Historic U.S. Fuel Ethanol Production.* http://www.ethanolrfa.org/industry/statistics. Washington, D.C.: Renewable Fuels Association.

Rowley, I. 2007. "Toyota's Bid for a Better Battery." *Business Week* Online. March 5. http://www.businessweek.com/magazine/content/07_10/b4024075.htm .

Stauffer, N. 2006. "Ethanol-Boosted Gasoline Engine Promises High Efficiency at Low Cost." Massachusetts Institute of Technology Laboratory for Energy and the Environment newsletter, October.

U.S. Congress. 2005. *Energy Policy Act of 2005*. Public Law 109–58. Washington, D.C.

Wall, E. 2007. "Plug-In Hybrid Electric Vehicle R&D Activity." Presentation at the U.S. Department of Energy PHEV Stakeholders Meeting, Washington, D.C., June 13. http://avt.inel.gov/pdf/phev/2_Wall_FCVT_Perspective.pdf.

Wang, M.Q. and M. Mintz. 2003. *Benefits and Costs of Hydrogen Fuels.* ANL/ESD/TM-163. http://www.transportation.anl.gov/pdfs/AF/270.pdf. Argonne, Ill.: Argonne National Laboratory, Center for Transportation Research.

Wang, M.Q., and D. Santini. 2006. "Energy and Greenhouse Gas Emission Impacts of Fuel Ethanol." Presentation at the LERDWG [Laboratory Energy R&D Working Group] Meeting, Washington, D.C., September 13.

White House, The. 2006. "Press Briefing on the President's Advanced Energy Initiative, Via Teleconference. Transcript." February 1. http://www.whitehouse.gov/news/releases/2006/02/20060201-6.html. Washington, D.C.: The White House, Office of the Press Secretary.

White House National Economic Council, The. 2006. *Advanced Energy Initiative.* http://www.house.gov/science/hot/Competitiveness/energy_initiative.pdf. Washington, D.C.: The White House.