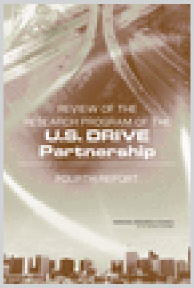

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REVIEW OF THE RESEARCH PROGRAM OF THE U.S. DRIVE PARTNERSHIP

Fourth Report

Committee on Review of the U.S. DRIVE Research Program, Phase 4
Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

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Preface

The current U.S. DRIVE (*D*riving *R*esearch and *I*nnovation for *V*ehicle Efficiency and *E*nergy Sustainability) Partnership was formed in 2011 and, although it has a different emphasis, it is similar in concept to its predecessors—the FreedomCAR and Fuel Partnership and the Partnership for a New Generation of Vehicles (PNGV). Thus, even though the present review is referred to as Phase 4—the fourth review of the old FreedomCAR and Fuel Partnership—it is the first review since the new U.S. DRIVE Partnership was formed. However, the charter for the new Partnership was released only in late February 2012, and neither the revised technical and cost targets nor the roadmap had been updated as of early March 2012.

From a practical standpoint, even though the change in emphasis toward nearer-term technologies (especially more electrification and a greater use of biofuels) was well known during the writing of the Phase 3 review,[1] the National Research Council's Committee on Review of the U.S. DRIVE Research Program, Phase 4, measured progress relative to the existing roadmap and targets. Even though individual targets will undoubtedly be updated by the new Partnership, changes for many technologies are likely to be small, and some probably will not be changed at all. Regardless of the target updates or lack thereof, a charge to the committee is to report on progress, especially between Phases 3 and 4. (The statement of task for the committee is presented in Chapter 1, in the section entitled "Committee Approach and Organization of This Report.") Moreover, since the charter for the newly formed U.S. DRIVE Partnership was only recently released,

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[1] National Research Council. 2010. *Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report.* Washington, D.C.: The National Academies Press.

observations on progress toward technical targets and target dates for almost all of the efforts between Phases 3 and 4 are based on existing FreedomCAR and Fuel Partnership targets.

The present review will be the only report for Phase 4 on the now U.S. DRIVE Partnership. The report provides an overview of the structure and management of the Partnership. Also discussed are adequacy and progress as well as major achievements and technical problem areas associated with the Partnership goals. The committee makes recommendations in those areas in which it sees the possibility of improvement.

Vernon P. Roan, *Chair*
Committee on Review of the U.S. DRIVE
Research Program, Phase 4

Acknowledgments

The Committee on Review of the U.S. DRIVE Research Program, Phase 4, wishes to thank the members of the U.S. DRIVE Partnership, all of whom contributed a significant amount of time and effort to this National Research Council (NRC) study by giving presentations at meetings, responding to requests for information, or providing valuable information. The committee especially thanks Christy Cooper, Director, U.S. DRIVE Partnership, Office of Vehicle Technologies, U.S. Department of Energy, for being so responsive to the committee's many requests for information. The chair also recognizes the committee members and the staff of the Board on Energy and Environmental Systems (BEES) for their hard work in organizing and planning committee meetings and their individual efforts in gathering information and writing sections of the report.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Jay Baron, Center for Automotive Research,
Paul Blumberg, NAE, Ford Motor Company (retired),
Andrew Brown, Jr., NAE, Delphi Corporation, and Chair, BEES,
Harry Cook, NAE, Ford Motor Company (retired),

Matthew Fronk, Matt Fronk and Associates,
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James F. Mathis, NAE, Exxon Corporation (retired),
Gary Rogers, FEV, Inc., and member, BEES,
Robert W. Shaw, Jr., Aretê Corporation, and
Richard Teets, Delphi Corporation (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lawrence T. Papay, NAE, PQR, LLC. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Tables, Figures, and Box

TABLES

FIGURES

BOX

Summary

This report by the National Research Council's (NRC's) Committee on Review of the U.S. DRIVE Research Program, Phase 4, follows three previous NRC reviews of the FreedomCAR and Fuel Partnership, which was the predecessor of the U.S. DRIVE Partnership (NRC, 2005, 2008a, 2010). The U.S. DRIVE (*D*riving *R*esearch and *I*nnovation for *V*ehicle Efficiency and *E*nergy Sustainability) vision, according to the charter of the Partnership, is this: "American consumers have a broad range of affordable personal transportation choices that reduce petroleum consumption and significantly reduce harmful emissions from the transportation sector." Its mission is as follows: "Accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles (LDVs), as well as related energy infrastructure" (U.S. DRIVE, 2012). The Partnership focuses on precompetitive research and development (R&D) that can help to accelerate the emergence of advanced technologies to be commercialization-feasible.

The guidance for the work of the U.S. DRIVE Partnership and the priority setting and targets for needed research are provided by joint industry/government technical teams. This structure has been demonstrated to be an effective means of identifying high-priority, long-term precompetitive research needs for each technology with which the Partnership is involved.

Technical areas in which research and development as well as technology validation programs have been pursued include the following:

- Internal combustion engines (ICEs) potentially operating on conventional and various alternative fuels,
- Automotive fuel cell power systems,
- Hydrogen storage systems (especially onboard vehicles),

- Batteries and other forms of electrochemical energy storage,
- Electric propulsion systems,
- Hydrogen production and delivery, and
- Materials leading to vehicle weight reductions.

In each of these technology areas, specific research targets have been established, although some targets and program emphases are undergoing revision. Program oversight is provided by an Executive Steering Group (ESG), which is not a federal advisory committee. It consists of the U.S. Department of Energy's (DOE's) Assistant Secretary for Energy Efficiency and Renewable Energy (EERE) and a vice-presidential-level executive from each of the Partnership companies. The DOE EERE efforts are divided between the Vehicle Technologies Program (VTP) and the Fuel Cell Technologies Program (FCTP). The Partnership collaborates with other DOE offices outside of EERE, as appropriate, and with the U.S. Department of Transportation on safety-related activities.

The U.S. DRIVE partners include four automotive companies, five energy companies, two electric power companies, and the Electric Power Research Institute, with the DOE providing the federal leadership. During the past year, several associate-member companies have also been added. The Partnership does not itself conduct or fund R&D, but each partner makes its own decisions regarding the funding and management of its projects.

Even though the technologies involved are not all under the U.S. DRIVE umbrella, the *potential* primary pathways to the long-term goals of significantly reduced petroleum consumption as well as reduced criteria emissions and reduced greenhouse gases (GHGs) for LDVs are as follows:

- Improved ICE vehicles coupled with greater use of biofuels and natural gas, with low life-cycle environmental impacts;
- A shifting of significant portions of transportation energy from petroleum to the electric grid through the expanded use of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs); and
- The possible transition to hydrogen as a transportation fuel utilized in hydrogen fuel cell vehicles (HFCVs).

The committee notes that none of these pathways is without issues and none is devoid of promise.

The development of biomass feedstocks and of the technologies for conversion to transportation fuels is outside the responsibility of U.S. DRIVE. Similarly, the impact on GHG emissions of a broad deployment of PHEVs and BEVs will depend on the deployment of a variety of low-criteria-pollutant and low-GHG-emissions electricity generation technologies, another area that is outside the purview of U.S. DRIVE. However, the transition to hydrogen fuel with low life-cycle GHGs is within the scope of U.S. DRIVE.

The scope of this review is to assess the progress in each of the technical areas, to comment on the overall adequacy and balance of the R&D effort, and to make recommendations that will help the Partnership meet its goals (see Chapter 1 for the statement of task for the committee). This Summary provides overall comments and a brief discussion of the technical areas covered more completely in the report and presents the committee's main conclusions and recommendations.

OVERALL COMMENTS

Adequacy and Balance

The three previous NRC reports (NRC, 2005, 2008a, 2010) reviewed funding for the FreedomCAR and Fuel Partnership and the allocation of that funding between hydrogen-related and non-hydrogen-related activities. Generally speaking, those reports concluded that the balance between technologies was largely appropriate. However, in the Phase 3 report (NRC, 2010), it was noted that major shifts in emphasis and funding had occurred. It was and is the view of the committee that high-risk, potentially high-payoff R&D is an appropriate expenditure of government resources. However, recent economic conditions influence what the committee and the government consider "appropriate." It is still believed by the committee that support for precompetitive research on long-term technologies such as the enablers for hydrogen to become a viable transportation fuel and the fuel cell R&D leading to affordable HFCVs is important and should be continued. At the same time, the committee continues to agree that government support for technologies that have impact both in the nearer and the longer terms, especially those that could transfer some of the required transportation energy from petroleum to biofuels or to the electric grid, is also appropriate.

Since the last review, distribution of the Partnership funding has shifted significantly, with the share for hydrogen-related activities having decreased continually from $200 million in fiscal year (FY) 2009 to $104 million in FY 2012. Over the same period, battery R&D funding in the VTP dedicated to U.S. DRIVE rose from $69 million to $90 million, and from $23 million to $31 million for advanced combustion R&D. The committee notes that other vehicle technologies receiving significant funding, such as more efficient electrical components and lighter-weight materials, would potentially benefit all future propulsion systems.

It is the view of this committee that, based on the current status and projected incremental improvements of existing technologies, none of them yet has the performance attributes and cost to dominate the market and to meet the goal of the large-scale replacement of petroleum use and the reduction of emissions. Therefore, it is appropriate to continue investing resources on the most impactful research and not to let resources dwindle so far as to be unable to sustain a critical mass required to support a robust decision on any technology. Thus, it is extremely important to choose both the most appropriate technologies and the right targets for each technology.

Progress and Barriers

Overall, technical progress since the previous NRC review has been steady, and there is evidence of solid progress in all areas; in some cases, the progress has been impressive. The Partnership is effective in moving toward its goals, and the technical teams have been an effective public-private partnering mechanism. However, equally notable are some of the remaining barriers. Good examples are fuel cells and onboard hydrogen storage. On the one hand, projected mass-manufacturing costs have continued their downward trend for automotive fuel cells at the same time that demonstrated durability has continued to rise. On the other hand, onboard hydrogen storage remains a formidable barrier, with no alternative yet proving to be better than compressed gas.

For BEVs and PHEVs, lithium-ion (Li-ion) batteries have made substantial progress and costs are declining, but there are formidable barriers to realizing batteries with the performance and cost attributes that would make these vehicles broadly successful in the U.S. marketplace.

In addition to cost and technical performance barriers, there are production and infrastructure barriers that must be resolved (e.g., the need for widespread affordable hydrogen if mass-produced HFCVs are to become a reality, a feedstock and production combination for biofuels that does not compete with food crops, and a low-carbon electric grid). For example, BEVs will require a recharging infrastructure that could likely be accelerated by government involvement. The same is true for a refueling infrastructure for HFCVs and natural gas. Indeed, without government involvement, a hydrogen refueling infrastructure is unlikely to be realized—which would greatly limit the acceptance of HFCVs (NRC, 2008b).

Program Management and Decision Making

As in previous NRC reviews of the FreedomCAR and Fuel Partnership, the committee finds the operation and management of the technical teams, and the integration of the systems analysis functions within those teams, to be exemplary for the most part. However, the application of systems analysis to strategic decision making is lagging, especially concerning alternative pathways to achieving objectives such as reduced U.S. petroleum consumption or GHG emissions. It is not apparent that critical issues being investigated by the technical teams are guided and prioritized by an overall program understanding of the scale and limits of these technical improvements and how they affect larger program goals. In addition, the results and implications of systems analyses conducted by the technical teams have crosscutting implications for research direction and goals throughout the program. The potential exists for implicit conflict among the respective goals of the various technical teams. It is imperative that the Partnership's ESG, Joint Operations Group, or other program decision-making groups continually broaden their understanding of these implications and adapt research plans as technology or other critical factors change so as to provide effective overall portfolio management.

The Phase 3 report expressed concern that the ESG, charged with overall Partnership guidance, had not met for almost 2 years, leaving an apparent vacuum in the realm of guidance at the senior-leadership level (NRC, 2010, p. 35). The ESG did finally meet for the first time in 4 years, in June 2011, and has scheduled annual meetings starting in October 2012. However, given the pace of relevant developments in both technology and policy, this meeting schedule seems barely adequate to "set high-level technical and management priorities for the Partnership" as specified in its charter (U.S. DRIVE, 2012). In summary, the Partnership's two systems analysis teams have done excellent work and have made great progress at the microlevel; nonetheless, although there are signs of improvement, it is still unclear to the committee whether and how this work is being adequately applied at the senior-leadership level within DOE or the Partnership to guide overall Partnership direction.

Recommendation S-1 (5-1 in Chapter 5). The Executive Steering Group should be engaged to set targets for the U.S. DRIVE Partnership that are consistent with the objectives of reduced petroleum consumption and GHG emissions, and U.S. DRIVE should conduct an overall review of the Partnership portfolio, both for the adequacy of the R&D effort to achieve the targets and for focus on the mission of supporting longer-term, higher-risk precompetitive activities in all three potential primary pathways.

Recommendation S-2 (2-1 in Chapter 2). The U.S. DRIVE Partnership should adopt an explicitly portfolio-based R&D strategy to help DOE to balance the investment among alternative pathways along with the more traditional reviews of the progress of individual pathways. Furthermore, this portfolio-based strategy should be based on overall systems analysis performed by a *proactive* vehicle systems and analysis technical team and fuel pathway integration technical team.

ADVANCED INTERNAL COMBUSTION ENGINES AND EMISSION CONTROLS

Advanced combustion and emissions control for ICEs are important because ICEs for transportation systems are going to be the dominant automotive technology for decades, whether in conventional vehicles, hybrid vehicles, PHEVs, or biofueled or natural gas vehicles. Because a better understanding of the combustion process and emissions production can help to overcome a major barrier to more advanced ICEs, this work is important to the country.

The advanced combustion and emission control technical team is making progress and doing a good job at maintaining a close and constructive working relationship with the stakeholders within the vehicle and energy community. It is critical for the technical team to maintain this collaboration and to look for ways to make it even stronger. Continued close collaboration between DOE and industry is necessary to allow newly developed understandings to transition into the industrial laboratories and for the identification of new areas in which enhanced understanding will be most beneficial.

The emergence of natural gas in apparently very large quantities is a factor that must also be considered in future visions of ICEs. Natural gas can be used directly as a fuel, it can be used as the feedstock to produce "drop-in" fuels that can replace gasoline or diesel, or it can be used to produce hydrogen. Indeed, the steam-reforming of natural gas is currently used for most hydrogen production. Natural gas is also used in electricity generation and could play a larger role in the future.

Recommendation S-3 (3-2 in Chapter 3). U.S. DRIVE should make an assessment of whether natural gas can be an enabler for achieving the advanced combustion modes currently being pursued in its research portfolio.

FUEL CELLS

Based on the advancements that the automotive companies have made on their hydrogen fuel cell vehicles and assuming that part of these advancements have been due to Partnership efforts, it can be said that significant progress has been made since the NRC Phase 3 report (NRC, 2010). Furthermore, investigations on fundamental issues related to durability and performance have been expanded in scope and have begun to yield insight not only into degradation mechanisms but also in terms of providing guidance for developing next-generation catalysts and electrodes, both of which are necessary to meet the performance and cost targets for fuel cells. Progress has been made in other areas as well, even though budgets have been reduced. It is unclear as to whether increased funding would have yielded additional advancements in the past 3 years, but it is clear that the current budget is having an effect on progress.

Fuel cell stack cost and durability are still the two major areas that have not simultaneously met targeted levels. Stack lifetimes have exceeded 50 percent of the targeted 5,000 hours in real-world on-road vehicles. Fuel cell costs for a 500,000-vehicle production level have been projected to have dropped since the last report, from \$60 to \$70/kW in 2009 to \$49/kW in 2011. Further reductions will potentially come over time, as learning from on-road vehicle performance and technologies with reduced platinum loadings are adopted. Advanced catalysts have been and continue to be developed, including platinum-free systems. Such programs have emanated from academia, industry, and, most important, from the national laboratories.

Statements by automotive companies in this country as well as by companies in other countries have indicated that vehicles in limited quantities will be placed in predetermined locations, partly gated by the availability of hydrogen refueling facilities, in the 2014-2016 time frame. This activity coincides with the timing of the original technology roadmap of the FreedomCAR and Fuel Partnership whereby in 2015 there would be a commercialization readiness decision. Considering the economic downturn and the budget constraints of late, the vehicle engineering accomplishments attest to the commitment of automotive manufacturers to fuel cell vehicles and thus to the importance of the Partnership's enabling R&D. The onset of HFCV deployment is impressive.

Recommendation S-4 (3-4 in Chapter 3). The DOE should increase efforts for the cost reduction initiatives for fuel cells taking into account the entire system, including balance of plant. Emerging modeling capabilities should be used for sensitivity analysis and for guiding resource allocation to the areas that will have the greatest impact on performance, endurance, and cost at the system level.

ONBOARD HYDROGEN STORAGE

Onboard hydrogen storage is a key enabler for HFCVs. The primary focus of the hydrogen storage program is to foster the development and demonstration of commercially viable hydrogen storage technologies for transportation and stationary applications. A specific goal of the program is a vehicle driving range of greater than 300 miles between refuelings while simultaneously meeting vehicle packaging, weight, cost, and performance requirements. The program also includes life-cycle issues, energy efficiencies, safety, and the environmental impact of the applied hydrogen storage technologies.

The physical storage of hydrogen on vehicles as compressed gas has emerged as the technology path for the early introduction of fuel cell vehicles. The hydrogen storage capacity using compressed hydrogen gas tanks is performance limiting for some vehicle architectures and is expensive, but it will apparently not prevent the introduction of HFCVs into the market. The storage capacity of current high-pressure tanks does not meet the long-term program targets, but it may be adequate for some applications for which the cost can be justified. On the basis of current work being undertaken on high-pressure storage tanks, the committee is optimistic that the cost of hydrogen storage tanks can be reduced in the future through reduced materials and manufacturing costs; however, cost reduction is not likely in the near term.

Much research was conducted by the (now phased out) three centers of excellence for hydrogen storage. These centers eliminated dozens of possibilities while identifying a few with potential for continued study. Although progress continues to be made in solid-state storage, key characteristics, required to meet targets, have not all been met with any single material. Cost is a significant barrier for all systems. Given the reductions in the hydrogen storage budget, the Partnership is not on a path to overcome these barriers. Basic research and generation of new ideas are needed. One example is the need for R&D on liner materials for cryo-compressed hydrogen storage. The discovery and development of materials for effective onboard hydrogen storage involve high-technical-risk R&D not likely to be accomplished without continued research attention and government funding.

Recommendation S-5 (3-11 in Chapter 3). The DOE (e.g., the Office of Basic Energy Sciences, the Office of Energy Efficiency and Renewable Energy, the Advanced Research Projects Agency-Energy) should initiate a new program that builds on the excellent progress made to date and expands into fundamentally new hydrogen storage research areas. A critical assessment of prospects for, and barriers to, advanced storage techniques and concepts should form *the first part* of this initiative.

ELECTROCHEMICAL ENERGY STORAGE

Improved electrochemical energy storage technologies, especially batteries and ultracapacitors, are critical to the advancement of both the Partnership's nearer-term and long-term goals: significant improvement in their performance and reduction in costs can result in greater electrification of vehicles. Electrochemical energy storage technology is a key enabler for all electric drive vehicles, including hybrid electric vehicles (HEVs), PHEVs, BEVs, and HFCVs. The past decade has seen the commercial development of HEVs, due in part to the already-successful development of high-power batteries supported by U.S. DRIVE through the United States Advanced Battery Consortium (USABC). Partially attributable to over a decade of extensive DOE-funded Li-ion battery R&D, this technology is now starting to show tangible commercial progress in several high-profile battery BEV and PHEV production programs. Additionally, Li-ion batteries are now also being commercialized in HEVs.

U.S. DRIVE programs have helped achieve cost reduction of Li-ion PHEV battery technology, with projections of $650/kWh at production volumes of 100,000 packs per year, and being on track for the $300/kWh target this decade. The lifetime of Li-ion battery technologies has been extended to 10 to 15 years and/or 3,000 to 5,000 deep cycles. Performance, life, and safety targets have been met for HEV batteries, with significant cost reductions allowing them to approach cost targets.

Key technical and cost barriers remain. Although costs are approaching targets for HEV applications, costs for BEV batteries are most problematic, exceeding targets by a factor of four or more. BEV batteries also have a serious barrier with respect to gravimetric and volumetric energy density, where a twofold improvement is needed. Safety remains an issue that needs continued diligence, especially with high-energy-density BEV batteries that tend to be volatile in response to abuse.

The electrochemical energy storage program is comprehensive and well organized and has achieved tangible success in its mission to develop high-power and high-energy electrochemical storage technology for electric drive vehicles. However, the technical targets for electrochemical energy storage systems are largely outdated and contain some significant inconsistencies and unclear constructions. The Phase 3 review recommended revision of the targets, but the Partnership did not act on this recommendation. Revision of the technical specifications can help direct funded and even unfunded R&D toward the most important issues in a more cost-effective way.

Recommendation S-6 (3-13 in Chapter 3). The USABC targets for BEV batteries are more than 20 years old and should be revised, as also recommended in the NRC's Phase 3 review. U.S. DRIVE should also undertake a diligent effort to develop a consistent set of technical targets across the key electric drive vehicle applications.

ELECTRIC PROPULSION AND ELECTRICAL SYSTEMS

Although modern automobiles are loaded with electrical and electronics components, from power windows to electronic fuel injection systems, many future automobiles will use electric motors in the driveline. Included will be power electronics and electrically driven accessories such as motor-driven air-conditioning compressors, electric power steering, and "smart" interfaces for battery charging. Vehicles will need higher-temperature semiconductors and/or advanced cooling techniques to minimize component size and weight and to maximize efficiencies. Components must be integrated with other components for lower costs and better space utilization. All of the above suggests the desirability of better modeling and computational techniques in addition to research for a better understanding of the fundamentals.

Major accomplishments in this area are a General Motors (GM) traction system that met all of the Partnership goals for 2010 and all of the goals except for cost for the 2015 targets. Also, a Delphi inverter with a General Electric (GE) motor appears to show higher power density and slightly lower cost, although it is not clear that it met the efficiency targets. Since efficiency, volume, and weight are interrelated, meeting just one target is not sufficient, although it does indicate progress. Several promising initiatives were undertaken in 2011. Significant barriers are cost, weight, volume, and efficiency, which the Partnership is effectively addressing. Power electronics and electrical machines have been developed over many years, and now significant improvements are needed. A significant issue that needs to be addressed is a thorough systems analysis to assign targets for efficiency, weight, volume, and cost. Ideally this should include the battery, fuel cell, and internal combustion engine so that the whole system can be optimized. Clearly this would involve separate targets for each type of vehicle, that is, for HEVs, PHEVs, BEVs, and HFCVs. Another issue is the cost and availability of the rare earth materials currently used in permanent-magnet motors.

Recommendation S-7 (3-15 in Chapter 3). The U.S. DRIVE Partnership should determine the potential and limitations of designing motors with permanent-magnet materials using less rare earth metal.

MATERIALS

The challenge to the materials technical team is to generate a cost-neutral 50 percent vehicle weight reduction. This target was unrealistic when set, and it remains unrealistic. A similar conclusion was stated in previous NRC reviews. Nevertheless, weight reduction is a crucial part of any balanced approach to achieving aggressive fuel consumption targets, and it will undoubtedly entail enhanced computational methods and widespread material substitution. The work being performed under the auspices of the Partnership appears to be properly focused on relevant initiatives. However, although these initiatives appear relevant, the committee questions whether they all satisfy the criteria of high-risk, precompetitive research judged appropriate for federal involvement. Competition has raged among the steel, aluminum, and composites automotive supply base for many years in an effort to achieve low-cost weight reduction by means of materials substitution, and the aluminum, magnesium, high-strength steel, and composites content of production vehicles has been steadily rising for more than 20 years. Furthermore, numerous vehicle demonstration projects have been conducted in the past, both by materials trade associations and by industry consortia, some of which were sponsored by DOE. Clearly, materials are important for many technologies that are part of the U.S. DRIVE Partnership.

Recommendation S-8 (3-18 in Chapter 3). The materials technical team should expand its outreach to the other technical teams to determine the highest-priority collective Partnership needs, and the team should then reassess its research portfolio accordingly. Any necessary reallocation of resources could be enabled by delegating some of the highly competitive metals development work to the private sector.

HYDROGEN

The Partnership in DOE's EERE includes the hydrogen production, delivery, and dispensing program and is part of the Fuel Cell Technologies Program (FCTP). The FCTP addresses a variety of means of producing hydrogen in distributed and centralized plants using technologies that can be made available in the short and long term. Even though hydrogen has been somewhat de-emphasized by the Obama administration, there are still three technical teams addressing these issues: the fuel pathway integration technical team, the hydrogen production technical team, and the hydrogen delivery technical team.

The hydrogen fuel and vehicle pathway integration effort looks across the supply chain from well (source) to tank. The goals of this effort are to (1) analyze issues associated with production, distribution, and dispensing pathways; (2) provide input on methodologies for setting targets for integrated pathways and pathway components; (3) identify needs and gaps in the hydrogen analysis effort; and (4) enhance communication of analysis parameters and results to improve consistency and transparency. Technology is available to produce and distribute hydrogen commercially, but not as a competitively priced transportation fuel. Research efforts are focused on (1) broadening the options available to produce hydrogen with low GHGs and (2) reducing the cost of distribution and dispensing.

The hydrogen production program embodies hydrogen generation from a wide range of energy sources, including natural gas, coal, biological systems, nuclear heat, wind, solar heat, and grid-based electricity; grid-based electricity employs several of these sources to varying extents, depending on geographical area. In the short term, when a hydrogen pipeline system is not in place, distributed generation in relatively small plants will be required to supplement truck-delivered hydrogen available from existing, large-scale commercial plants.

Approaches to hydrogen generation using processes based on commercial experience include coal and biomass gasification and water electrolysis. The DOE had a program, completed in 2009, to improve natural gas reforming. Commercial options now exist to generate hydrogen either in distributed or centralized plants using natural gas.

The production of hydrogen from coal and/or biomass offers a relatively mature technology. Reasonable estimates of the timing of vehicular hydrogen demand suggest that hydrogen production from new, large-scale coal and/or biomass facilities will not be needed before 2020 (NRC, 2008b). Capital cost is a critical issue with either gasification process. In addition, the cost and availability of carbon sequestration are critical with regard to the use of coal, and feedstock cost and availability are critical with regard to the use of biomass.

The Partnership recognizes that water electrolysis may play an important role in the hydrogen infrastructure and is supporting numerous promising electrolysis efforts to reduce capital and operating costs. In addition, DOE is pursuing the use of wind-generated energy for electrolysis to reduce carbon dioxide emissions. Nuclear energy is also a possible source that would not produce significant amounts of GHGs. The DOE is also investigating several approaches to hydrogen production that are in an early stage of R&D and which have the potential to reduce energy requirements for hydrogen production. They include photoelectrochemical and high-temperature thermal water splitting, and biological generation.

A significant factor in fuel cost is the means for delivering, storing, and dispensing hydrogen. In a fully developed hydrogen economy, the postproduction part of the supply system for high-pressure hydrogen will probably cost as much and consume as much energy as production does (NRC/NAE, 2004).

In the past 2 years there have been significant achievements in hydrogen production and distribution. The projected cost of transport by tube trailers has been reduced by 40 to 50 percent. In addition, the feasibility of using electrochemical compression of hydrogen instead of expensive mechanical compression has been established, providing a path for further cost reduction.

Recommendation S-9 (4-1 in Chapter 4). The DOE should seek the strategic input of the Executive Steering Group (ESG) of U.S. DRIVE. The ESG could provide advice on all DOE fuel programs potentially critical to providing the fuel technologies needed in order for advanced vehicle technologies to achieve reductions in U.S. petroleum dependence and greenhouse gas emissions, and DOE should subsequently make appropriate program revisions to address user needs to the extent possible.

Regardless of the source of hydrogen, it is clear that for there to be the possibility of widespread HFCVs, there must be the availability of hydrogen for refueling.

GRID IMPACTS OF ELECTRICITY AS AN ENERGY SOURCE FOR VEHICLES

The inclusion of battery electric vehicles and plug-in hybrid electric vehicles in U.S. DRIVE makes it important to consider the impact of such vehicles on the electric grid. Reasonable forecasts of market penetration indicate that the increased national energy demands appear unlikely to challenge the capacity of the U.S. electric grid. However, much evidence suggests that clustering of PHEV and BEV owners could result in local loads that exceed the capacity of local transformers, especially for fast charging during hours of peak electricity use. DOE leadership in close collaboration with current and future providers of electricity will be critical to the timely and effective resolution of these issues.

BIOFUELS AND THE PARTNERSHIP

Within DOE, the Biomass Program has the responsibility for managing the development and progress for the bulk of the needs for biofuels, including biomass production, feedstock logistics, and biomass conversion to biofuel. Historically DOE focused on end use through the Partnership. This split of focus puts the responsibility for making and delivering biofuels with the Biomass Program, and R&D for the LDV drive train with the Partnership.

Starting in 2010 the Biomass Program reduced its ethanol programs and increased its programs for making biofuels that are indistinguishable from petroleum-based products, sometimes called drop-in fuels, which do not require special ICE technology or distribution systems. These can be produced as gasoline, jet fuel, or diesel-type finished products. Biomass sources include woody biomass and energy crops. Considering a scenario in which the role of ethanol is diminished, a U.S. DRIVE focus on ICE development that can handle drop-in fuels and other biofuels is warranted.

NATURAL GAS AND THE PARTNERSHIP

Although natural gas and light-duty vehicles using compressed natural gas (CNG) are not part of the U.S. DRIVE effort, R&D on CNG storage tanks and on refueling systems is being addressed by DOE's Advanced Research Projects Agency-Energy (ARPA-E) in its Methane Opportunities for Vehicular Energy (MOVE) program.

Recommendation S-10 (4-7 in Chapter 4). U.S. DRIVE should include the CNG vehicle and possible improvements to its analysis efforts in order to make consistent comparisons across different pathways and to help determine whether CNG vehicles should be part of its ongoing vehicle program.

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Introduction

BACKGROUND

During the past few decades, the U.S. government, either through the administration or the Congress, has generally addressed the supply of energy and its use to meet national goals of energy independence, national security, minimizing environmental impact, and, more recently, minimizing greenhouse gases (GHGs) and enhancing sustainability (NAS/NAE/NRC, 2009b). The emphasis on one or another of these goals changes depending on the Congress and/or the administration, but in recent years all have been of interest.

The transportation sector and the use of light-duty vehicles (automobiles and light trucks) are almost completely dependent on petroleum, a significant fraction of which is imported; this dependence presents energy and economic security issues (EIA, 2012). Further, the combustion of petroleum-derived fuels, mostly gasoline and diesel, in transportation produces a significant fraction of the nation's greenhouse gases, as well as such criteria pollutants as oxides of nitrogen, non-methane hydrocarbons, and particulate matter that affect local air quality (EIA, 2012). And in recent years, the price volatility of gasoline and diesel fuel has had significant economic impacts on the transportation sector, the automotive industry, the economy, and vehicle owners.

The U.S. government during the past few decades has enacted legislation and policies to help achieve its national goals in the transportation sector. For example, the Corporate Average Fuel Economy (CAFE) regulations have increased and are projected to further increase the average miles per gallon (mpg) for light-duty vehicles, while federal emissions standards have led to a dramatic decrease in criteria vehicle emissions per mile traveled.[1] The increasing levels of CAFE standards will create a market pull for advanced technologies that will increase the relevance of technology development in the U.S. DRIVE (*D*riving *R*esearch and *I*nnovation for *V*ehicle Efficiency and *E*nergy Sustainability) Partnership. Other legislation seeks to promote the replacement of petroleum-based fuels with alternative fuels, such as those derived from biomass (NRC, 2011a). The federal government also invests in research and development (R&D) to help enable advanced vehicle and fuel technologies to emerge in the commercial marketplace (NRC, 2011b), which could help to address the nation's energy security, economic, and environmental challenges. In fact, the U.S. Department of Energy (DOE) developed a broad set of strategies in its Quadrennial Technology Review (QTR) to address the nation's energy challenges, including electrifying the vehicle fleet and increasing vehicle efficiency (DOE, 2011). However, the challenges of doing so are great.

In addition to the federal legislation noted above, California has programs to reduce emissions of greenhouse gases (GHGs) from vehicles, one of which is the Zero Emission Vehicle Program. The state is promoting the adoption of zero-emission vehicles (ZEVs)—for example, electric vehicles and fuel cell vehicles—by setting benchmarks for 2020 and 2025 for infrastructure to support such vehicles as well as for the adoption of such vehicles. The governor of California announced in Executive Order B-16-2012 that the aim is for there to be 1.5 million ZEVs in California by 2025, with supporting infrastructure and a growing market.[2] This program is also stimulating development of the advanced vehicle technologies that are under development in the U.S. DRIVE Partnership.

U.S. DRIVE PARTNERSHIP

This report contains the results of a review by the National Research Council's (NRC's) Committee on Review of the U.S. DRIVE Research Program, Phase 4. Although the government/industry partnership known as U.S. DRIVE was formed in 2011 as the committee was just beginning its review, the Partnership is very much in line with the partnerships that preceded it, namely, the FreedomCAR and Fuel Partnership and, prior to that, the Partnership for a New Generation of Vehicles (PNGV). The NRC reviewed the PNGV seven times, from 1993 to 2001, and the FreedomCAR and Fuel Partnership three times, between 2004 and 2010. (See previous NRC reports for background on the partnerships, the various

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[1] In 2010, CAFE standards were enacted requiring light-duty vehicles (passenger cars and light trucks) to meet 35.5 mpg by model year (MY) 2016. In 2012 a proposed CAFE rule was issued requiring 56 mpg for passenger cars and 40.3 for light trucks by MY 2025. The average combined fuel economy for light-duty vehicles in 2011 was 27.3 mpg. See http://www.nhtsa.gov/fuel-economy.

[2] For more information, see the California Air Resources Board ZEV Program at http://www.arb.ca.gov/msprog/zevprog/zevprog.htm.

technical areas, and issues that those partnerships, similar to U.S. DRIVE, have addressed [NRC, 2001, 2005, 2008a, 2009, 2010a].)

The DOE has been involved for more than three decades in R&D programs related to advanced vehicular technologies and alternative transportation fuels. Under the Clinton administration during the 1990s, much of this R&D was conducted under the PNGV program. This initial peacetime government/auto industry partnership was formed between the federal government and the auto industry's U.S. Council for Automotive Research (USCAR).[3] The PNGV sought to improve the nation's competitiveness significantly in the manufacture of future generations of vehicles, to implement commercially viable innovations emanating from ongoing research on conventional vehicles, and to develop vehicles that achieve up to three times the fuel efficiency of comparable 1994 family sedans (DOE, 2004a,b; NRC, 2001; PNGV, 1995; The White House, 1993).

Although the PNGV focused on achieving a significant increase in fuel economy for a family sedan and resulted in three concept vehicles unveiled at the end of that program, under President George W. Bush a shift in the program took place toward addressing the challenges of using hydrogen fuel and fuel cell vehicles. The FreedomCAR and Fuel Partnership[4] was established to address these challenges and to advance the technology enough so that a decision on the commercial viability of hydrogen vehicles could be made by 2015. As the Obama administration took office in early 2009, a redirection began to take place, with reduced R&D on hydrogen and fuel cell vehicles and increased attention directed toward technologies for the use of electricity to power light-duty vehicles, with emphasis on plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles (or battery electric vehicles [BEVs]). The Obama administration views BEVs and PHEVs as a nearer-term technology and has a goal of enabling the deployment of 1 million electric drive vehicles on the road by

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[3] USCAR, which predated PNGV, was established by Chrysler Corporation, Ford Motor Company, and General Motors Corporation. Its purpose was to support intercompany precompetitive cooperation so as to reduce the cost of redundant R&D, especially in areas mandated by government regulation, and to make the U.S. industry more competitive with foreign companies. Chrysler Corporation merged with Daimler Benz in 1998 to form DaimlerChrysler. In 2007, DaimlerChrysler divested itself of a major interest in the Chrysler Group, and Chrysler LLC was formed, which is now Chrysler Group LLC.

[4] In February 2003, before the announcement of the FreedomCAR and Fuel Partnership, President Bush announced the FreedomCAR and Hydrogen Fuel Initiative to develop technologies for (1) fuel-efficient motor vehicles and light trucks, (2) cleaner fuels, (3) improved energy efficiency, and (4) hydrogen production, and a nationwide distribution infrastructure for vehicle and stationary power plants, to fuel both hydrogen internal combustion engines and fuel cells (DOE, 2004a). The expansion of the FreedomCAR and Fuel Partnership to include the energy sector after the announcement of the initiative also supports the goal of the FreedomCAR and Hydrogen Fuel Initiative. The partners in the program included DOE, USCAR, BP America, Chevron Corporation, ConocoPhillips, ExxonMobil Corporation, and Shell Hydrogen (U.S.). During 2008, with increased interest in plug-in hybrid electric vehicles and battery electric vehicles, the electric utilities DTE Energy (Detroit) and Southern California Edison were added.

2015. As discussed in Chapter 5 of the present report, the American Recovery and Reinvestment Act of 2009 (Public Law 111-5) provided significant funding outside of U.S. DRIVE to stimulate investment in the electrification of vehicles. The DOE also turned to nearer-term applications, such as forklifts, for fuel cells. In 2011, the FreedomCAR and Fuel Partnership morphed into U.S. DRIVE, and a U.S. DRIVE Partnership Plan was formally released in February 2012 (U.S. DRIVE, 2012).

Building on the participation in the previous partnerships, currently U.S. DRIVE includes the following partners:

- *Automobile industry:* U.S. Council for Automotive Research LLC (USCAR, the cooperative research organization for Chrysler Group LLC, Ford Motor Company, and General Motors Company) and Tesla Motors;
- *Electric utility industry:* DTE Energy Company, Southern California Edison Company, and the Electric Power Research Institute (EPRI);
- *Federal government:* U.S. Department of Energy; and
- *Fuel industry:* BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US.

According to U.S. DRIVE (2012), the Partnership is a nonbinding, nonlegal, voluntary government/industry partnership. It does not itself conduct or fund R&D, but each partner makes its own decisions regarding the funding and management of its projects. By bringing together technical experts and providing a framework for frequent and regular interaction, the Partnership provides a forum for discussing precompetitive, technology-specific R&D needs, identifies possible solutions, and evaluates progress toward jointly developed technical goals. Its frequent communication among partners also helps to avoid duplication of efforts and increases the chances of successful commercialization of publicly funded R&D.

The U.S. DRIVE (2012) vision is that

> American consumers have a broad range of affordable personal transportation choices that reduce petroleum consumption and significantly reduce harmful emissions from the transportation sector.

Its mission is to

> Accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

The Partnership addresses the development of advanced technologies for all light-duty passenger vehicles: cars, sport utility vehicles (SUVs), pickups, and minivans. It also addresses technologies for hydrogen production, distribution, dispensing, and storage, and the interface and infrastructure issues associated with the electric utility industry for the support of BEVs and PHEVs. Furthermore, as noted in the NRC's Phase 3 report, the activities and success of the Partnership "can serve as an inspiration and motivation for the next generation of scientists and engineers, and thus contribute to restoring American leadership in research and its application for the public good" (NRC, 2010a, p. 18).

In late 2011 the NRC appointed the Committee on Review of the U.S. DRIVE Research Program, Phase 4 (see Appendix A for biographical information on the committee members). Its report represents a continuing review by the NRC of the research programs of the partnerships that have been formed to address advanced light-duty vehicle and associated infrastructure challenges. The main charge to the committee for this report is to review activities since the third review of the FreedomCAR and Fuel Partnership (NRC, 2010a). (The full statement of task for the committee is provided below in this chapter.) The first review was conducted during 2004-2005 and the second review during 2007-2008, resulting in the Phase 1 and Phase 2 reports (NRC, 2005, 2008a). (These previous NRC reviews of the FreedomCAR and Fuel Partnership will be referred to here as the Phase 1, 2, or 3 reviews or reports.)

SCOPE, GOALS, AND TARGETS

The long-term vision of the Partnership is to enable the emergence in the marketplace of light-duty passenger vehicles that will significantly reduce petroleum consumption and harmful emissions. One can envision, if technology development is successfully introduced into commercially viable light-duty vehicles, a pathway starting with more fuel-efficient internal combustion engines (ICEs) and hybrid electric vehicles (HEVs), including PHEVs, use of all-electric-drive vehicles, the deployment of biofueled ICE vehicles, and the deployment of fuel cell vehicles with onboard hydrogen storage as well as the addition of an infrastructure for supplying hydrogen to these vehicles (see Figure 1-1).[5] The Partnership works on issues at the vehicle/electric grid interface but is not directly involved with electricity production technologies. The Partnership also works toward ensuring an adequate electricity infrastructure to provide recharging energy for PHEVs and BEVs; such an infrastructure would clearly be essential, for example, if a major shift in PHEV and/or BEV vehicle sales were to take place. To this end, the Partnership works with other DOE offices that sponsor some research to ensure that such an infrastructure is in place when needed, or to learn what it will take to ensure that it can be in place when needed.

If biofuels are to supply a significant portion of the U.S. transportation fuel needs, the infrastructure for the harvesting of biomass, its conversion, and

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[5] William Peirce, General Motors, "Vehicle Operations Group Perspective on U.S. DRIVE," presentation to the committee, December 5, 2011, Washington, D.C.

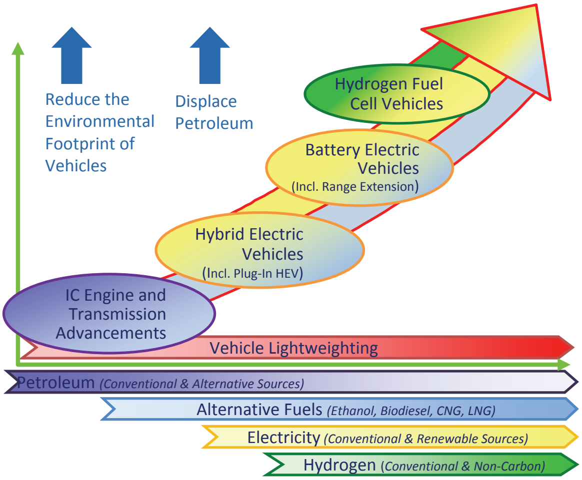

FIGURE 1-1 A technology vision of how vehicles and fuels may evolve over time, leading to reduced petroleum consumption and emissions. SOURCE: William Peirce, General Motors, "Vehicle Operations Group Perspective on U.S. DRIVE," presentation to the committee, December 5, 2011, Washington, D.C.

its wide-scale distribution, probably by pipelines, will have to be put in place (NAS/NAE/NRC, 2009a,b; NRC, 2008b, 2011a). However, the Partnership is not directly involved in the production or feedstock issues for biomass-based fuels, which are addressed by DOE's Biomass Program. The Partnership has been more directly involved in hydrogen production technologies needed for fuel cell vehicles, but in this case as well, many such technologies at large scale have been under the guidance of programs that are not part of the Partnership, such as DOE's Office of Nuclear Energy (NE) or its Office of Fossil Energy (FE). Thus hydrogen-fueled fuel cell vehicles, plug-in or all-electric vehicles, and biofueled vehicles all will have to face infrastructure issues and hurdles to varying degrees. The initial costs of new technologies, which are much higher than the high-volume costs, are an impediment to commercialization, and the timing of the deployment of vehicles and the supporting infrastructure are important issues. These are especially important given that companies must show a profit within a reasonable time. The government can work with the private sector to help reduce these barriers to commercialization.

The Partnership examines a portfolio of pathways and precompetitive technologies in four broad categories, all of which include potential issues related to the technologies and/or fuels (U.S. DRIVE, 2012):

1. *Vehicles:*
   - Advanced combustion and emissions control,
   - Fuel cells,

   - Electrochemical energy storage (e.g., batteries),
   - Electric drive and power electronics,
   - Lightweight materials, and
   - Vehicle systems and analysis.
2. *Fuels:*
   - Hydrogen production,
   - Hydrogen delivery,
   - Fuel pathway integration, or
   - Other sustainable mobility fuels as agreed to by the Partnership.
3. *Joint vehicles/fuels:*
   - Hydrogen codes and standards, and
   - Hydrogen storage.
4. *Joint vehicles/electric utility:*
   - Electric grid interaction.

To address the technical challenges associated with the envisioned pathways, the Partnership has established quantitative performance and cost targets[6,7] for precompetitive technologies. These targets and the research related to their attainment are discussed later in this report. Given some of the changes in focus of the U.S. DRIVE Partnership as compared with some of its predecessors, some targets for individual technologies are being reevaluated by the Partnership. Technical teams, as noted in the next section, "Organization of the Partnership," specify and manage technical and crosscutting needs of the program.

ORGANIZATION OF THE PARTNERSHIP

The Partnership consists of a number of oversight groups and technical teams that have participants from government and industry (see Figure 1-2). The Executive Steering Group, which is not a federal advisory committee, is responsible for the governance of the Partnership and is made up of the DOE Assistant Secretary for the Office of Energy Efficiency and Renewable Energy (EERE) and a vice-presidential-level executive from each of the Partnership companies. Each of the three industry-related operations groups—the Vehicle Operations Group, the Fuel Operations Group, and the Electric Utility Operations Group—meets regularly on a schedule to suit the group's own needs. The Joint Operations Group meets on a regular basis to bring together the participants of the three operations groups for exchanges of information and discussion of issues. This structure is very much the same as existed in the FreedomCAR and Fuel Partnership (DOE, 2004c, 2009;

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[6] DOE defines "goals" as desired qualitative results that collectively signify Partnership mission accomplishments. It defines "targets" as tangible quantitative metrics to measure progress toward goals.

[7] All references to cost imply estimated variable cost (or investment, as appropriate) based on high volume (500,000 annual volume) unless otherwise stated. "Cost" refers to the cost of producing an item, whereas "price" refers to what the consumer would pay.

NRC, 2008a, 2010a; U.S. DRIVE, 2012; also see Chapter 2 for further discussion of the organization and of Partnership decision making).

As with previous partnerships, the U.S. DRIVE Partnership also has industry/government technical teams (see Figure 1-2) responsible for setting technical and cost targets as well as focusing appropriate R&D on the candidate subsystems. Most of these technical teams focus on specific technical areas, but some, such as the hydrogen codes and standards technical team and the vehicle and systems analysis technical team, focus on crosscutting issues. A technical team consists of scientists and engineers with technology-specific expertise from the automotive companies, energy partner companies, utility industry companies, and national laboratories, as well as DOE technology development managers. Team members may come from other federal agencies if approved by the appropriate operations group(s). A technical team is responsible for developing R&D plans and roadmaps, reviewing research results, and evaluating technical progress toward meeting established research goals (U.S. DRIVE, 2012). Its discussions are restricted to nonproprietary topics.

The U.S. DRIVE Partnership has also expanded its outreach compared with the FreedomCAR and Fuel Partnership by including associate members representing nonpartner organizations. All but three technical teams have at least one associate member. These associate members will bring additional technical

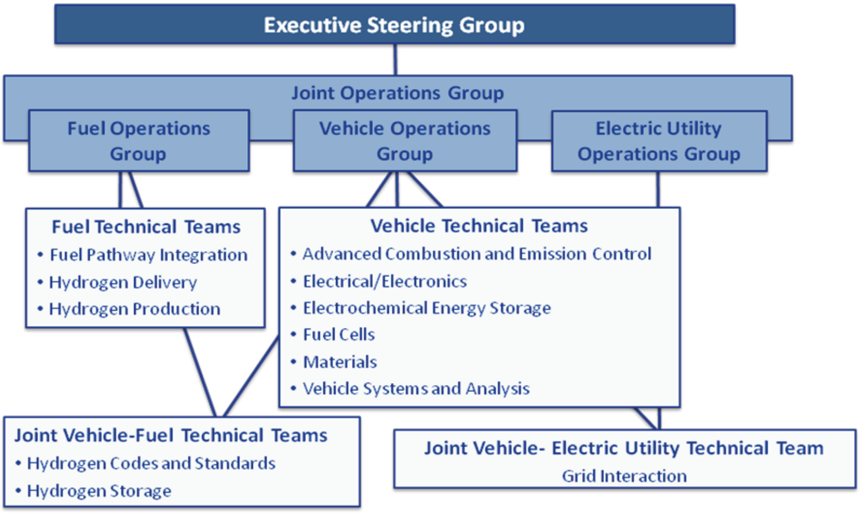

FIGURE 1-2 The organizational structure of the U.S. DRIVE Partnership. NOTE: OEM, original equipment manufacturer. SOURCE: C. Cooper, Department of Energy, "U.S. DRIVE Overview Presentation," presentation to the committee, December 5, 2011, Washington, D.C.

expertise and knowledge to the technical teams. (See Chapter 2 for a discussion of which associate members have been included.)

The various vehicle technical teams focus on fuel cells, advanced combustion and emissions control, systems engineering and analysis, electrochemical energy storage, materials (especially on lightweight materials), and electrical systems and power electronics. The three fuel technical teams address hydrogen production, hydrogen delivery, and fuel/vehicle pathway integration. There are two joint technical teams connecting the fuel teams and the vehicle teams: an onboard hydrogen storage team and a codes and standards team. The utility interface issues have resulted in a relatively new technical team related to electricity, namely, the grid interaction technical team.

At the DOE, primary responsibility for the U.S. DRIVE Partnership rests with the EERE.[8] The two main program offices within EERE that manage the Partnership are the Vehicle Technologies Program (VTP) and the Hydrogen and Fuel Cell Technologies Program (HFCTP).

The VTP mission is “to develop and promote energy-efficient and environmentally friendly transportation technologies that will enable America to use significantly less petroleum and reduce greenhouse gas (GHG) emissions while meeting or exceeding drivers’ performance expectations and environmental requirements” (DOE, 2012). In addition to R&D for light-duty vehicle technologies, the VTP also works with technologies applicable to medium- and heavy-duty vehicles through the 21st Century Truck Partnership.[9] The VTP addresses such areas as (1) vehicle and systems simulation and testing, (2) advanced combustion engine R&D, (3) batteries and electric drive technology, (4) materials technology, and (5) fuels technology.

The HFCTP’s mission is “to enable the widespread commercialization of hydrogen and fuel cell technologies, which would reduce petroleum use, GHG emissions, and criteria air pollutants and contribute to a more diverse energy supply and more efficient energy use” (DOE, 2012). It directs R&D activities on fuel cells, hydrogen fuel, manufacturing and distribution, and technology validation.

Some activities that are not part of U.S. DRIVE but that are related to the HFCTP focus are not within the EERE. The Office of Fossil Energy has supported the development of technologies to produce hydrogen from coal and to capture and sequester carbon. The Office of Nuclear Energy has in previous years supported research into the potential use of high-temperature nuclear reactors

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[8] The EERE has a wide variety of technology R&D programs and activities related to renewable energy technologies, ranging from the production of electricity from solar energy or wind and the production of fuels from biomass, to the development of technologies to enhance energy efficiency, whether for vehicles, appliances, buildings, or industrial processes. It also has programs on distributed energy systems (see Appendix C for an EERE organizational chart).

[9] The DOE supports several other programs related to the goal of reducing dependence on imported oil. The 21st Century Truck Partnership supports R&D on more-efficient and lower-emission commercial road vehicles. The NRC has conducted two reviews of that program (NRC, 2008c, 2012).

to produce hydrogen, while the Office of Science (SC) supports fundamental work on new materials for storing hydrogen, catalysts, fundamental biological or molecular processes for hydrogen production, fuel cell membranes, and other related basic science areas (DOE, 2004d,e). Within the EERE there also is a Biomass Program, which is not part of the U.S. DRIVE Partnership. However, biomass is of interest to the Partnership, both as one possible source of hydrogen as well as of biomass-based liquid transportation fuels (e.g., ethanol or gasoline or diesel derived from biomass) and as part of a strategy to diversify energy sources for the transportation sector; thus there is cooperation between the Partnership and the Biomass Program. The committee believes, as discussed in this report and as mentioned in the Phase 3 report (NRC, 2010a), that improving ICE vehicles using biomass-based fuels is an important part of the portfolio of vehicle technologies that needs to be addressed. And now, the increased emphasis on vehicle electrification suggests that understanding the interface between electric vehicle technology and the electric utility sector is of even greater importance. The DOE's Office of Electricity Delivery and Reliability, which focuses on the U.S. electric transmission and distribution system, is therefore another office that needs to interface with the Partnership's efforts. This office is a separate office, as is the EERE, within the Office of the Under Secretary of Energy.

A PORTFOLIO OF VEHICLE AND FUEL TECHNOLOGIES

A long-term goal of the Obama administration and of the DOE's Office of Energy Efficiency and Renewable Energy is to "cut the Nation's greenhouse gas emissions in the range of 17 percent below 2005 levels by 2020, and 83 percent by 2050" (DOE, 2012). This includes all sectors of the economy, but to achieve such a goal will require that light-duty vehicles achieve significant reductions in petroleum use and corresponding GHG emissions. Other goals directly related to the technologies under development in U.S. DRIVE are these: "Invest in developing electric vehicles technologies enabling one million electric drive vehicles on the road by 2015" and "reduce oil imports by 1/3 by 2025" (DOE, 2012). Another EERE goal, although not directly related to technologies under development in U.S. DRIVE, is to "generate 80 percent of the Nation's electricity from a diverse set of clean energy sources by 2035" (DOE, 2012). If a large-scale penetration of BEVs or PHEVs takes place, then the goal of reducing GHGs significantly by 2050 will require an electricity production system that reduces such emissions significantly compared to the current U.S. electric power system.

The main technology pathway options for reducing petroleum use and GHG emissions from light-duty vehicles are the following:

- *Reduce Vehicle Fuel Consumption:* Improve the fuel economy of light-duty vehicles through improved technologies, hybridization, light-weighting, and other vehicle design approaches in order to reduce both the amount of petroleum used per mile of travel and the associated GHG emissions.

- *Use Non-Petroleum-Based Liquid Fuels in Internal Combustion Engines (ICEs):* Use alternatives to petroleum-derived gasoline and diesel fuels in ICE-powered vehicles. Such fuels could include various alcohols (such as ethanol, methanol, or butanol) derived either from such non-petroleum feedstocks as coal, natural gas, biomass, or garbage, or "synthetic" gasoline or diesel fuel derived from these feedstocks. The particular feedstocks and technologies used for the fuel production will determine the extent to which GHG emissions are reduced throughout the full fuel cycle.
- *Use Natural Gas in ICEs:* Use natural gas in ICE-powered vehicles. This reduces GHGs as compared to those from petroleum-based fuels, but the reduction in GHGs achieved will be less than for fuels that could be derived from non-carbon-based feedstocks or carbon-neutral biomass.
- *Use Hydrogen in ICEs or Fuel Cells:* Hydrogen can be used in either an ICE or a fuel cell. Much of the work by DOE in the partnerships has focused on developing better fuel cells and technologies for hydrogen production. If hydrogen is produced with low GHG emissions, then the full fuel cycle can have a low GHG footprint.
- *Use Electricity in BEVs or PHEVs:* A BEV would use no other energy source onboard the vehicle except for electricity from a battery, and a PHEV would travel some distance on electricity but would also have an ICE that would burn fuel. Both types of vehicles would obtain the electricity from the electric power system, and their GHG emissions would depend on the extent to which the electric power grid is de-carbonized, the number of miles that the vehicles could travel on electricity alone, the feedstock used for the production of the fuel used in the ICE on the PHEV, and the overall design of the vehicle for energy-efficient operation.

It is likely that in the coming decades there will be a diversity of vehicles and fuels that are commercialized. Some options are lower risk and nearer term than others, and they all face different technical, cost, and market risks. These issues have been explored in depth in other reports and will not be repeated here (see, for example, NAS/NAE/NRC, 2009a,b; NRC, 2008a,b; NRC, 2009; NRC, 2010a,b; NRC, 2011a,b; NRC/NAE, 2004). These studies have concluded that, given the high-risk and uncertain nature of many of these technologies and the immense challenge of achieving deep reductions in GHGs and petroleum use, an R&D insurance strategy pursuing a portfolio of possible technological options is the most prudent approach.

ROLE OF THE FEDERAL GOVERNMENT

As noted in the recent NRC (2012) report on a review of the 21st Century Truck Partnership, the role of the federal government in R&D varies depending on the administration and the Congress and the issues that they deem important for the nation to address. An extensive economics literature on the subject points to the importance of R&D to promote technical innovation, especially for research for which the private sector finds it difficult to capture the returns on its investment; this is especially true for basic research, the results of which can be broadly used. Such innovation, if successful, can foster economic growth and productivity, with improvements in the standard of living (Bernanke, 2011). Furthermore, in the energy area, the government generally has to confront issues of national security, environmental quality, or energy affordability. Many of these issues are addressed through policy initiatives or regulations, which place a burden on private firms to achieve. Thus there is a role for the federal government in supporting R&D, not only to help the private sector achieve these policy goals but also to help U.S. firms remain competitive in the face of international competition.

The committee believes that the federal government plays an important role in the development of technologies that can help to address government policies and regulations aimed at reducing emissions and fuel consumption from light-duty vehicles. Such efforts as the U.S. DRIVE Partnership and the 21st Century Truck Partnership are examples of public-private efforts to support R&D and to develop advanced technologies for vehicles. As noted by the NRC (2012), public-private partnerships generally include a variety of efforts (fundamental research, development, demonstration, and in some cases deployment). The federal government can support fundamental research through the national laboratories and universities, and industry can focus on development. The importance of having government/industry collaboration is that the private sector can help to transform improvements from research into cost-effective and marketable products. Generally, the contracting that is engaged in with the private sector is cost-shared, and research contracts more closely associated with fundamental or basic research will have a majority of federal funding, whereas contracts with a strong development or product component will have significant support from the private sector. In its recommendations in each of the technical areas, the committee has considered what activities are precompetitive and are most appropriate for U.S. DRIVE and federal government support. Implicit in all of the recommendations that relate to the support of additional research, the committee believes that the federal government has a role in the R&D.

COMMITTEE APPROACH AND ORGANIZATION OF THIS REPORT

The statement of task for this committee is as follows:

> The National Academies' National Research Council (NRC) Committee on Review of the Research Program of the FreedomCAR and Fuel Partnership [U.S. DRIVE Partnership], Phase 4, will address the following tasks:
>
> 1. Review the challenging high-level technical goals and timetables for government and industry R&D efforts, which address such areas as (a) integrated systems analysis; (b) fuel cell power systems; (c) hydrogen storage systems; (d) hydrogen production and

distribution technologies necessary for the viability of hydrogen-fueled vehicles; (e) the technical basis for codes and standards; (f) electric propulsion systems; (g) lightweight materials; (h) electric energy storage systems; (i) vehicle-to-grid interaction; and (j) advanced combustion and emission control systems for internal combustion engines.

2. Review and evaluate progress and program directions since the NRC's Phase 1, 2, and 3 reviews towards meeting the Partnership's technical goals, and examine ongoing research activities and their relevance to meeting the goals of the Partnership.
3. Examine and comment on the overall balance and adequacy of the research and development effort, and the rate of progress, in light of the technical objectives and schedules for each of the major technology areas.
4. Examine and comment, as necessary, on the appropriate role for federal involvement in the various technical areas under development, especially in light of activities ongoing in the private sector or in the states.
5. Examine and comment on the Partnership's strategy for accomplishing its goals, especially in the context of ongoing developments across the portfolio of advanced vehicle technologies (e.g, biofuels, plug-in hybrid electric vehicles, electric vehicles), the recent enactment of legislation on corporate average fuel economy standards for light-duty vehicles, and possible legislation on carbon emissions. Other issues that the committee might address include: (a) program management and organization; (b) the process for setting milestones, research directions, and making go/no-go decisions; (c) collaborative activities needed to meet the Partnership's goals (e.g., among the various offices and programs in DOE, the U.S. Department of Transportation, USCAR, the fuels industry, electric power sector, universities, and other parts of the private sector [such as venture capitalists], and others); and (d) other topics that the committee finds important to comment on related to the success of the Partnership to meet its technical goals.
6. Review and assess the actions that have been taken in response to recommendations from the NRC's previous reviews of the Partnership.
7. Write a report documenting its conclusions and recommendations.

The committee met four times to hear presentations from DOE and industry representatives involved in the management of the program and to discuss insights gained from the presentations and the written material gathered by the committee, and to work on drafts of its report (see Appendix D for a list of committee meetings and presentations). The committee established subgroups to investigate specific technical areas and formulate questions for the U.S. DRIVE program leaders to answer. These subgroups were organized as follows:

Subgroup on Program Decision Making:
Bernard Robertson, *Lead*
R. Stephen Berry
David L. Bodde
David E. Foster
Linos Jacovides
Constantine Samaras

Subgroup on Advanced Combustion Engines
and Emissions Control:
David E. Foster, *Lead*

Harold H. Kung
Bernard Robertson
Kathleen C. Taylor

Subgroup on Electrochemical Energy Storage:
Dennis A. Corrigan, *Lead*
Kathryn Bullock
Gerald Gabrielse
Linos Jacovides
Harold H. Kung
Robert J. Nowak
Brijesh Vyas

Subgroup on Fuel Cells:
Glenn A. Eisman, *Lead*
Dennis A. Corrigan
Gene Nemanich
Robert J. Nowak
R. Rhoads Stephenson
Kathleen C. Taylor
Brijesh Vyas

Subgroup on Electric Propulsion, Electrical Systems, and Power Electronics:
Linos Jacovides, *Lead*
Kathryn Bullock
Dennis A. Corrigan
Constantine Samaras
R. Rhoads Stephenson
Brijesh Vyas

Subgroup on Materials and Supplier Issues:
Bernard Robertson, *Lead*
Dennis A. Corrigan
Glenn A. Eisman
W. Robert Epperly
Kathleen Taylor

Subgroup on Hydrogen Production and Delivery (including Off-Board Storage):
W. Robert Epperly, *Lead*
R. Stephen Berry
David L. Bodde

Glenn A. Eisman
Harold H. Kung
Gene Nemanich

Subgroup on Onboard Hydrogen Storage:
Kathleen C. Taylor, *Lead*
R. Stephen Berry
Dennis A. Corrigan
Gene Nemanich
R. Rhoads Stephenson

Subgroup on Biofuel and Natural Gas Issues:
Gene Nemanich, *Lead*
David L. Bodde
David E. Foster
Gerald Gabrielse
Gene Nemanich
Constantine Samaras

Subgroup on Electric Grid/Vehicle Charging Issues:
David L. Bodde and Kathryn Bullock, *Leads*
Linos Jacovides
Constantine Samaras
Brijesh Vyas

Subgroup on Safety, Codes and Standards:
R. Rhoads Stephenson

Subgroup on Environmental Impacts:
Constantine Samaras, *Lead*
R. Rhoads Stephenson

The committee subgroups also held several conference calls and site visits to collect information on technology development and other program issues. The subgroups also met with the Partnership technical team leaders to clarify answers to questions and better understand the team dynamics, and several committee subgroups visited different companies to gain insight on the status of various technologies (see Appendix D). The Partnership also provided responses to the recommendations from the Phase 3 report, and these are included in the National Academies public access file. Budget information included in this report was collected from presentations made to the committee as well as from information provided by the Partnership to committee questions. The information gathered enabled the committee to compose its report and reach consensus on its entire report.

The Summary presents the committee's main conclusions and recommendations. This chapter (Chapter 1) provides background on the Partnership and on its organization. Chapter 2 examines the important crosscutting issues that the program is facing. Chapter 3 looks more closely at R&D for the various vehicle technologies, and Chapter 4 examines R&D for hydrogen production, distribution, and dispensing, as well as issues related to the use of biofuels and electricity for use in vehicles. Finally, Chapter 5 discusses the adequacy and balance of program efforts in the Partnership.

The structure of the chapters varies because of their different respective areas of focus. Chapter 2 addresses crosscutting issues, and those subjects do not have a technology development focus with specific milestones against which to assess progress, but the sections do address the importance of these issues to the success of the Partnership in meeting its goals, as well as discussing how well the Partnership has responded to the Phase 3 report recommendations.

The sections in Chapter 3 follow, for the most part, a structure that addresses, consistent with the statement of task, the following: (1) brief background on activities, budgets, and discussion of the technology and its importance to the goals of the program; (2) the current status of technologies vis-à-vis goals and targets; (3) an assessment of progress and key achievements; (4) significant barriers and issues that need to be addressed; (5) the response to recommendations from the Phase 3 review; (6) the appropriate federal role; and (7) recommendations.

Chapter 4 addresses the energy carriers for advanced vehicles, some of which, like hydrogen, are within the purview of the U.S. DRIVE Partnership and others, such as natural gas and biofuels, which are not. The chapter comments on status, progress, and response to Phase 3 recommendations for those areas that are part of the Partnership and makes recommendations for future efforts. Chapter 5 is a short chapter that comments, as in previous reports and as required by the statement of task, on the overall adequacy and balance of the program.

In addition to the appendixes referred to above (committee biographical information, the EERE organizational chart, and the list of meetings and presentations), Appendix B reprints the recommendations from the Phase 3 report, and Appendix E defines the report's acronyms and abbreviations.

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2

Crosscutting Issues

This chapter addresses crosscutting issues that are important to the success of the Partnership in meeting its goals. They have all been commented on in the National Research Council's (NRC's) Phase 1, 2, and 3 reviews, and much of the background is not repeated here (NRC, 2005, 2008, 2010). In this Phase 4 review, the committee emphasizes those issues that still require attention. The areas addressed here are (1) program decision making; (2) safety, codes and standards; (3) the grid interaction technical team (GITT), which addresses the interface between electric vehicles (EVs) and the electric grid; and (4) environmental implications of alternative pathways.

PROGRAM DECISION MAKING

Overview

The topics of strategic planning, program management, and decision making within the U.S. DRIVE Partnership are all closely related, and they all critically depend on systems analysis. As described in Chapter 1, the Partnership is a research and development (R&D) program that focuses on critical transportation technology and fuel challenges for vehicles; if successfully met, these challenges could significantly lower U.S. petroleum consumption and greenhouse gas (GHG) emissions while continuing to meet stringent criteria pollutant standards. The Partnership's individual technical teams, which include members from the U.S. Department of Energy (DOE), national laboratories, the automotive original equipment manufacturers (OEMs), energy companies, and power companies, work primarily at the vehicle component level and on the production, distribution, and delivery of hydrogen; in addition, there is recent attention on the interface between the nation's electricity delivery system and the charging of EVs (e.g., plug-in hybrid electric vehicles [PHEVs] or battery electric vehicles [BEVs]). There are annual DOE program reviews, in addition to many DOE-sponsored conferences and workshops, as well as their considerable participation in professional society conferences, to help keep all participants on the Partnership technical teams well informed. To these teams are added a vehicle systems and analysis technical team (VSATT) and a fuel pathway integration technical team (FPITT) that is focused on hydrogen. This organizational structure (shown in Figure 1-2 in Chapter 1) is based on project activities that focus on individual technical issues, as well as on total vehicle system integration and the total fuel chain. In addition, there is a need in the Partnership for a broader strategic perspective, which ostensibly the Executive Steering Group (ESG) provides. The system integration and performance issues require a systems analysis approach on several levels, necessitating a variety of systems analysis tools.

Systems Analysis

In its previous reports, the NRC recommended substantial activity to develop systems analysis tools to help the Partnership meet its goals. For example, in the NRC Phase 1 report, it was recommended that "an ongoing, integrated, well-to-wheels assessment be made of the Partnership's progress toward its overall objectives" (NRC, 2005, p. 9). In the NRC Phase 2 report, it was recommended that "the DOE should accelerate the development and validation of modeling tools that can be used to assess the roles of various propulsion systems and vehicle technologies and fuels, and utilize them to determine the impact of the various opportunities on the overall Partnership goals of reducing petroleum use and air pollutant and greenhouse gas emissions" (NRC, 2008, p. 13).

In the Phase 3 report, it was recognized that the Partnership had made substantial progress on the development and application of these systems analysis tools, that "well-to-wheels" (or "source-to-wheels") analysis was now routinely used across the Partnership, and that modeling and simulation tools were widely used within the technical teams (NRC, 2010, p. 34). In the current review, the committee found continued widespread use of systems analysis tools, including the migration to using the Autonomie model developed under a Cooperative Research and Development Agreement (CRADA) between the Argonne National Laboratory (ANL) and General Motors (GM), with architecture based on the Powertrain Systems Analysis Toolkit (PSAT) model described in the Phase 3 report. Overall, the development and deployment of systems analysis tools and models at the vehicle and fuel pathway level continue to be impressive and fully responsive to the committee's specific prior recommendations. However, the VSATT and FPITT systems analysis teams operate in a reactive support role to the individual technical teams: indeed, in the transition from the FreedomCAR and Fuel Partnership to U.S. DRIVE, the VSATT adopted "a renewed focus as a service organization to the other technical teams."[1] The application of systems analysis to the overall guidance and management of the Partnership and the determination of technical directions in pursuit of the Partnership's overarching goals relating to U.S. petroleum consumption and GHG emissions continue to be much less transparent. In the Phase 2 report (NRC, 2008, p. 30), it was noted that "there is no lack of technical review of the individual program elements, but what is missing is analysis of the quantitative impact on the overall goals of reducing petroleum use and pollutant and greenhouse gas emissions." In the Phase 3 report, it was observed that, despite some encouraging progress, "this remains an area in which the committee strongly encourages additional emphasis" (NRC, 2010, p. 35).

Once again, whereas the committee finds the operation of the technical teams and the integration of the systems analysis functions within those teams to be exemplary, the application of systems analysis to strategic decision making is lagging, especially concerning alternative pathways to achieving objectives such as reduced U.S. consumption of petroleum and reduced production of GHGs (see Chapter 1 for a brief discussion). It is not apparent that critical issues being investigated by the technical teams are guided and prioritized by an overall program imbued with an understanding of the scale and limits of these technical improvements and how they affect larger program goals. Additionally, the results and implications of systems analyses conducted by the technical teams have crosscutting implications for research direction and goals throughout the program. The potential exists for implicit conflict among the respective goals of the various technical teams: for example, simply seeking the highest-efficiency electric drive components may incur costs that would be better spent on alternative battery chemistry, and these trade-offs can only be made across the Partnership, driven by systems analysis. (It appears that industry is making these kinds of trade-offs in its own in-house decisions by, for example, sometimes adopting induction motors instead of more efficient but more costly permanent-magnet [PM] motors.)

Another example is the acceptance by U.S. DRIVE of 70 MPa (10,000 psi) as the de facto hydrogen storage tank pressure, on the premise that "higher density is better." This acceptance occurred without any apparent overall systems analysis considering not only onboard storage objectives, but also such factors as required compression energy, tank weight and cost trade-offs, or infrastructure ramifications. Consideration of all relevant factors could conceivably lead to the conclusion that, say, 8,000 psi would represent a better overall compromise. It is imperative that the Partnership's ESG, Joint Operations Group, or other program decision-making group continually strive to understand such implications and adapt research plans as technology or other critical factors change: in effect, provide overall portfolio management.

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[1] L. Slezak, Department of Energy, "Vehicle Systems and Analysis Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

As a part of the committee's work, it reviewed the electrical storage projects currently managed by DOE's Advanced Research Projects Agency-Energy (ARPA-E). ARPA-E is beyond the scope of U.S. DRIVE; indeed it is not even part of DOE's Office of Energy Efficiency and Renewable Energy (EERE), in which the U.S. DRIVE activities reside, but these projects complement the U.S. DRIVE technology portfolio. It is noteworthy that ARPA-E features, by design, an aggressive portfolio management approach. The committee believes that the U.S. DRIVE Partnership could benefit by exploring and applying some aspects of this portfolio approach, to address both system-wide trade-offs and uncertainty in the externalities affecting the program.

Portfolio Strategy for Managing Uncertainty

Each pathway for vehicle technology and its associated fuel supply (electricity, hydrogen, or liquids) poses unique near-term and long-term uncertainties. Many of the policies and actions that affect these pathway uncertainties reside beyond the influence of the U.S. DRIVE Partnership, yet their outcomes strongly influence the cost, marketplace attractiveness, and policy desirability of the competing pathways. This kind of context uncertainty cannot be eliminated, but rather must be managed by the U.S. DRIVE Partnership.

For example, the timing and extent of any transition to a low-carbon U.S. electricity system cannot reasonably be predicted. Yet this transition will strongly influence the cost and environmental impact of the electric vehicle (EV) pathway, and to a lesser extent that of hydrogen produced through electric energy. Or consider a second example of contextual uncertainty—the cost of natural gas. If natural gas supplies prove as abundant and inexpensive as some forecasts hold, then this resource could become the chief source of hydrogen well beyond the transition period. But if these estimates prove overly optimistic for reasons that cannot now be known, then some alternative will have to be developed. The issue for the U.S. DRIVE Partnership is how much to rely on natural gas and how much to invest in some hedged alternative, the classical dilemma of context uncertainty.

Much evidence shows that research management under context uncertainty is best accomplished through a portfolio strategy that balances risks and potential benefits across alternative futures, for example, by a consideration of uncertainties about technological progress and U.S. energy system characteristics. In the development of such a strategy, special attention should be paid to contextual scenarios that have differing impacts across several technology and fuel pathways. These portfolios can be informed by analytic methods such as real options analysis, scenario planning, or expert elicitation.

Recommendation 2-1. The U.S. DRIVE Partnership should adopt an explicitly portfolio-based R&D strategy to help DOE to balance the investment among alternative pathways along with the more traditional reviews of the progress of individual pathways. Furthermore, this portfolio-based strategy should be based on overall systems analysis performed by a *proactive* vehicle systems and analysis technical team and fuel pathway integration technical team.

The Phase 3 report expressed concern that the ESG, charged with overall Partnership guidance, had not met for almost 2 years, leaving an apparent vacuum in the realm of guidance at the senior-leadership level (NRC, 2010, p. 35). The ESG did finally meet for the first time in 4 years, in June 2011, and has scheduled annual meetings starting in October 2012. However, given the pace of relevant developments in both technology and policy, this meeting schedule seems barely adequate to "set high-level technical and management priorities for the Partnership" as specified in its charter (U.S. DRIVE, 2012).

In summary, the two systems analysis teams have done excellent work and have made great progress at the microlevel. Nonetheless, despite signs of improvement, it is still unclear to the committee how and whether this work is being adequately applied at the senior-leadership level within DOE or the Partnership to guide overall Partnership direction.

Scope of the Partnership

In the evolution of the Partnership from the Partnership for a New Generation of Vehicles (PNGV) through U.S. DRIVE's immediate predecessor, the FreedomCAR and Fuel Partnership, to the U.S. DRIVE Partnership, the scope and nature of the Partnership have changed considerably. The PNGV involved seven federal government agencies, with the Department of Commerce in the lead, whereas the U.S. DRIVE Partnership is led exclusively by DOE. The PNGV had specific objectives unique to the Partnership; U.S. DRIVE has a broader set of general goals, which are shared by other DOE programs and initiatives. In the words of the U.S. DRIVE Partnership Plan, published in February 2012:

> It is a non-binding, non-legal, voluntary government-industry partnership focused on advanced automotive and related energy infrastructure technology research and development (R&D). Specifically, the Partnership facilitates pre-competitive *technical information exchange* [emphasis added] among experts who interact as equal partners to discuss R&D needs, develop joint goals and technology roadmaps, and evaluate R&D progress. The Partnership itself does not conduct or fund R&D; each partner makes its own decisions regarding the funding and management of its projects. (U.S. DRIVE, 2012)

In light of the above, it is difficult to separate the activities and results directly attributable to U.S. DRIVE and those resulting from other complementary initiatives by DOE and/or the industry partners. Some of these complementary activities, such as the 21st Century Truck Program (21CTP), which pursues similar technologies applicable to heavy-duty vehicles, are subject to separate NRC review. The committee requested clarification from DOE as to which of these activities should be considered within the U.S. DRIVE Partnership for the purposes of this review. Table 2-1 was provided by DOE in response to this request.

Despite this difficulty, which is discussed further in Chapter 5, "Adequacy and Balance of the Partnership," the activities of the individual technical teams appear to be well focused and directed, as noted above. However, the network of potentially complementary or overlapping DOE-sponsored initiatives almost places DOE in a "systems integrator" role, without a transparent overall decision-making process.

Under the preceding PNGV structure, there was a clear process for consensus decision making, and a schedule of "downselects" as various candidate technologies either achieved their goals or were discarded. With the evolution through the FreedomCAR and Fuel Partnership to the U.S. DRIVE Partnership, no such comparable process appears to exist. With the exception of a steady reduction in funding for hydrogen and fuel cell activities (from roughly 70 percent at the begin-

TABLE 2-1 Alignment of Activities in Department of Energy (DOE) Programs and Their Relationship to U.S. DRIVE

DOE Program	DOE Subprogram/ Budget Line Item	U.S. DRIVE Technical Area
Hydrogen and Fuel Cell Technologies	Fuel Cell Systems R&D	Fuel Cells
	Hydrogen Fuel R&D	Hydrogen Production
		Hydrogen Delivery
		Hydrogen Storage
	Safety, Codes and Standards	Codes and Standards
	Systems Analysis	Fuel Pathway Integration
	Technology Validation	[a]
	Market Transformation	[a]
	Education	[a]
	Manufacturing R&D	[a]
Vehicle Technologies	Batteries and Electric Drive R&D	Electrochemical Energy Storage Electrical/Electronics
	Vehicle Systems, Simulation and Testing	Vehicle Systems Analysis Grid Interaction
	Advanced Combustion Engine R&D	Advanced Combustion and Emission Control
	Materials Technology	Materials
	Fuels Technologies	Not formally included in U.S. DRIVE
	Outreach, Deployment and Analysis	Not formally included in U.S. DRIVE

NOTE: R&D, research and development.

[a] Not formally included in the U.S. DRIVE Partnership.

SOURCE: Provided to the committee by DOE in response to committee questions.

ning of FreedomCAR to approximately 20 percent in the FY 2013 DOE budget request; see Chapter 5, Table 5-3), the majority of the candidate technologies and pathways in the Partnership portfolio continue to be supported some 10 years later, with no visible signs of the application of overall systems analysis or other high-level management to focus the efforts on technologies and pathways with the greatest chance of success. The rather amorphous nature of the U.S. DRIVE Partnership and the need to consider market and commercialization factors in overall portfolio management make the role of the Executive Steering Group critical.

Recommendation 2-2. The Executive Steering Group (ESG) should meet regularly and provide the necessary guidance and leadership in developing strategy and programs to meet goals for the reduction of greenhouse gases and petroleum dependence. Furthermore, the ESG should insist that all analyses conducted by and for the U.S. DRIVE Partnership reflect the system-wide full life cycle.

Associate Members and Supply-Chain Participation

Participation in the FreedomCAR and Fuel Partnership, now the U.S. DRIVE Partnership, has expanded to include an additional automotive OEM, energy companies, and electric utilities. Most recently, the technical teams are adding selected associate members to bring additional perspective and expertise. As of April 24, 2012, the Partnership had selected the following nine associate members, with three more yet to be named:

- *Advanced combustion and emission control technical team associate member:*
  — Michigan State University
- *Codes and standards technical team associate member:* Not yet announced
- *Electrical and electronics technical team associate member:*
  — Deere & Company
- *Electrochemical energy storage technical team associate member:* Not yet announced
- *Fuel cell technical team associate member:*
  — Rochester Institute of Technology
- *Fuel pathway integration technical team associate member:*
  — Air Products and Chemicals
- *Grid interaction technical team associate members:*
  — Northeast Utilities
  — Tennessee Valley Authority
  — Midwest Independent Transmission System Operator, Inc. (MISO)
- *Hydrogen delivery technical team associate member:*
  — Praxair

- *Hydrogen production technical team associate member:*
  — SunCatalytix
- *Hydrogen storage technical team associate member:*
  — University of Michigan
- *Materials technical team associate member:*
  — Morgan Olson Corporation
- *Vehicle systems and analysis technical team associate member:* Not yet announced

The committee sees much to be gained from the addition of associate members, for two reasons: (1) additional membership can expand the scope of technology opportunities available to the U.S. DRIVE Partnership, and (2) additional membership can expedite commercial application of new technologies by connecting the U.S. DRIVE Partnership more completely with the automotive supply chain, where commercial innovation increasingly occurs.

Although the new additions of associate members are surely a promising beginning, they seem to consist largely of universities and large companies. In contrast, new emerging ventures are less well represented, yet such companies could bring significant value for the reasons discussed below.

Over the past 15 years a new competitive dynamic has emerged among R&D-intensive industries like road mobility: it involves a rapid growth in arrangements for the exchange of new technologies, new products, and new services. Automotive OEMs and suppliers typically formalize these arrangements as joint R&D ventures, licensing (and cross-licensing) of intellectual property, and joint production arrangements.

Three closely linked characteristics of the business environment motivate these exchanges: the growing cost of maintaining a vertically integrated R&D program, the need for speed in moving vehicles to market, and the desire to become profitable at low production volumes. As a consequence, research and development, innovation, and scale-up are increasingly accomplished throughout the supply chain, and greater than 50 percent of the value added in automobiles is now provided by suppliers. Many OEMs are reaching out to the entrepreneurial sector through in-house venture funds.

This emerging architecture suggests that the U.S. DRIVE Partnership could benefit from greater participation by companies in the supply chain, which would improve program guidance and increase the pace at which the technologies developed by R&D are brought to market.

Recommendation 2-3. The U.S. DRIVE Partnership should continue its inclusion of innovative supply-chain companies and should expand this approach to emerging entrepreneurial companies with relevant technological capabilities. When new entrepreneurial ventures are being considered for associate membership, the committee recommends a systematic vetting process much like the "due diligence" process of venture-capital investors.

SAFETY, CODES AND STANDARDS

The safety, codes and standards (SCS) activity is focused exclusively on safety issues related to hydrogen. R&D is conducted in selected areas and DOE provides technical expertise to several standards development organizations (SDOs). SDO committees are generally staffed by interested volunteers and follow American National Standards Institute (ANSI) procedures on consensus building and voting for approval. Draft standards are available in several areas (hydrogen vehicles, hydrogen storage systems, and fueling stations), but few have been finalized. In some areas (e.g., hydrogen storage tanks) there is an international effort to create a global technical regulation (GTR) that will be adopted by individual countries.

Significant progress in the development of safety-related codes and standards has been made over the past several years. Several standards organizations (e.g., the Society of Automotive Engineers [SAE], CSA America, the International Organization for Standardization [ISO], and others) have issued draft or Technical Information Reports (TIRs), but few have finalized, approved standards. Extensive testing of Type 1 high-pressure (steel) tanks for forklifts and other industrial trucks has occurred. Risk-based quantitative risk assessment has been extended from fueling station separation distances to tunnels and indoor refueling. The SAE hydrogen (H_2) tank standard (J2579) has become the basis for the recently issued draft Global Technical Regulation (GTR) (SAE, 2009; Nguyen, 2010).

The current goal of the codes and standards technical team is to have all necessary hydrogen standards (for both vehicles and fueling infrastructure) in place by 2020. Given that most of the major automotive OEMs have announced plans for a limited introduction of hydrogen fuel cell vehicles (HFCVs) in the 2014-2016 time period, this goal should be accelerated if possible. Unfortunately the budget for this program has decreased from more than $15 million in FY 2008 to just $5 million in the proposed FY 2013 budget. There is still substantial work to be done to finalize these standards and to show by experiment that they will provide adequate public safety when large numbers of vehicles are deployed.

The initial rollout of HFCVs is expected to be small (a few hundred to a few thousand vehicles), and the vehicles will be sold in areas that already have fueling infrastructure. These areas are expected to be in Japan, Germany, California, Hawaii, and maybe South Korea. Clusters of stations will then expand in additional geographic areas along with connecting links between clusters on major highways. For this reason it is desirable to accelerate the finalization of codes and standards to the 2014-2016 time frame.

There are several efforts in the hydrogen storage area to reduce the cost and weight of high-pressure H_2 tanks. The lower limit of both cost and weight will undoubtedly be set by safety considerations. This will inevitably require an extensive and rigorous tank testing program to ensure that adequate safety margins are maintained.

An extensive testing program was carried out by Sandia National Laboratories on Type 1 (steel) tanks for industrial trucks. The safety standards that have been developed (like SAE J2579) have not been validated with sufficient tests to ensure that they will separate good tanks from bad tanks. Further safety testing needs to be done with Type 3 and 4 tanks. (Type 3 tanks have metallic liners and composite fiber overwraps, and Type 4 tanks have plastic liners and composite fiber wraps.)

Response to Recommendations from the Phase 3 Review

The Partnership agreed with the SCS recommendations in the NRC (2010) Phase 3 review except for two of these recommendations. It did not agree with establishing an emergency response R&D program for alternative fuels because it does not consider that to be precompetitive R&D. Historically the hydrogen codes and standards technical team has exclusively covered HFCVs and hydrogen fueling stations. Apparently the Partnership and the associated codes and standards technical team are unwilling to follow the Phase 3 recommendations to expand their scope to cover the entire fuel pathway from source to vehicle, or to cover other vehicle/fuel types, including electric vehicles. Perhaps another team or office needs to be formed to address the end-to-end (well-to-wheels) safety analysis and to make sure that *all* of the regulations, codes, and standards (RCSs) are in place.

Appropriate Government Role

It is not only appropriate but essential that the government fund the majority of the RCS development, adoption, and domestic and international harmonization. These are unlikely to be accomplished by industry alone (although industry provides a great deal of volunteer labor to the various safety committees).

Recommendations

The most recent plans of the SCS program have the goal of having the RCSs ready by 2020. This delay from earlier goals was likely caused by budget cuts in recent years. Stations are being built now (in certain areas), and commercial leases and sales of HFCVs may begin as early as 2014.

Recommendation 2-4. The Partnership should place a much higher priority on the safety, codes and standards (SCS) program and accelerate the date for final regulations, codes, and standards to 2014. The committee still recommends that, if the budget allows, the scope of the SCS program be expanded to cover all vehicle/fuel combinations being considered by DOE. This would include natural gas, battery electric vehicles, plug-in hybrid electric vehicles, biofuels, and other combinations that are appropriate.

Further safety testing of high-pressure tanks is needed.

Recommendation 2-5. The Partnership should plan and execute a tank testing program for the Type 3 and Type 4 tanks that are expected to be used in passenger vehicles.

The program has done extensive fuel cell testing to determine allowable limits on impurities in the H_2 fuel. This is appropriate for the high-pressure, compressed-gas tanks that are expected to be used initially.

Recommendation 2-6. As candidate materials are identified, the Partnership should expand the safety, codes and standards program to identify new contaminants that may be given off by adsorbent or chemical storage systems. These activities should be coordinated with the Storage Systems Center of Excellence at the Savannah River National Laboratory.

Over the years the SCS program has supported some H_2 sensor development for stationary applications (fueling stations). No work has been done on low-cost sensors for vehicle installation.

Recommendation 2-7. The Partnership should consider phasing out and turning over to industry for commercialization the stationary H_2 sensor effort that has been supported for several years and consider starting a new program on inexpensive H_2 sensors for vehicles.

Electric and/or hydrogen vehicles can pose a hazard to emergency responders. How do the responders protect themselves from a vehicle that has been extensively damaged by a crash or fire?

Recommendation 2-8. The Partnership should consider starting a hydrogen vehicle emergency response R&D effort similar to that now being conducted for electric and plug-in vehicles. One of the issues that should be studied is how to depressurize a damaged tank.

THE GRID INTERACTION TECHNICAL TEAM

Mission

The mission of the grid interaction technical team is to support a transition scenario to large-scale electrified vehicle charging with transformational technology, proof of concept, and information dissemination. A collaborative effort is underway to address the interests of U.S. DRIVE partners and other stakeholders so as to identify and support the reduction of barriers to the large-scale introduction of grid-connected vehicles.

Scope

The scope of the GITT work is interaction between light-duty vehicles that have to "plug in" to the grid to recharge their batteries (e.g., in general, EVs that are light-duty BEVs or PHEVs), the charging infrastructure, and the electric power grid, focusing on the following key areas:

- Electric distribution and smart-grid interface,
- Interface of the "plug-in" vehicle to the local power distribution network,
- Government policy impact analysis,
- Consumer usability, and
- Life cycle and total cost of ownership.

Major Challenges and Barriers

The GITT lists its major challenges and barriers as follows: (1) developing and verifying EV-grid connectivity and communication, (2) enabling EV-grid interoperability, and (3) facilitating the development of regional standards and recommendations. Challenges and possible barriers to standards development are regional standards, such as "GB standards"[2] from China and recommendations such as those of the European Automobile Manufacturers' Association (ACEA) in Europe. The GITT has recently had some success in supporting global cooperation and harmonizing standards and component compatibility. Examples are cooperative agreements between the United States and the European Union and between the United States and China, joint activities such as pilot projects to facilitate common standards, and the development of standards for laboratory test procedures and protocols. Additional attention to identifying and remedying security vulnerabilities of communications for EV supply equipment (EVSE) hardware and software is warranted. The team could play a part in this research.

Plans and Implementation

The R&D tasks and projects of the GITT are focused on near-term implementation with long-term impact. In addition to continuing its support of codes and standards, the team's present agenda includes the following:

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[2] GB standards are the Chinese national standards issued by the Standardization Administration of China.

- Cost reduction,
- Convenient charging, and
- Smart charging and communications.

Results

A model streamlining process is ready to be adapted and used by local governments, installers, and inspectors for permitting and inspecting residential charging stations.

The development and demonstration of measurement and communications modules are laying a foundation for measurement and communication within the vehicle and between the vehicle and home and energy service providers. An end-use measurement device (EUMD) accurately measures energy consumption and communicates with the energy service provider/home area network (HAN). Two-way messaging from the vehicle to the EVSE and the HAN, the smart meter, and the distribution transformer has been demonstrated.

Organization and Contacts

In addition to the national laboratories noted in this section, the main participants in the GITT work currently are the U.S. Council for Automotive Research (USCAR), DTE Energy, Southern California Edison, Tesla, and the Electric Power Research Institute (EPRI).

The National Renewable Energy Laboratory (NREL) is one of the leading participants in this work. The NREL, ANL, Idaho National Laboratory, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory are also working with the Society of Automotive Engineers to support the development effort by supplying reference materials to chairing committees, and developing hardware, test fixtures, and testing equipment.

Future Plans

Top priorities for the GITT work are now focused on the needs and technical issues of developing the EV-grid interface. They are as follows:

- Demonstrate communication and control of direct current (dc) charging,
- Verify and validate cybersecurity standards,
- Develop a prototype wireless charging test fixture,
- Update the EUMD,
- Develop communication and control of off-board wireless charging electronics, and
- Directly support SAE standards committees.

Budget

The DOE budget for activities supporting grid integration objectives in FY 2011 was $1.9 million (estimate based on "shared" elements of DOE's Vehicle Systems budget) and an estimated $2.0 million for FY 2012.

Outreach and Partnerships

The GITT participants have leveraged their collective resources well by participating through the SAE and other professional organizations in the development of standards for battery charging. It also coordinates the efforts of standards organizations and groups that are developing hardware. These activities are necessary and should be continued as the smart grid and electric vehicle power systems continue to develop.

One outreach, however, seems underdeveloped by the GITT—that is, engaging the state regulatory agencies that control the economic incentives for electric utility companies. By regulating the price that can be charged for electric service, these agencies can provide powerful incentives for retail customers to use electricity at the most economic and environmentally friendly times. In the case of plug-in vehicles using Level 1 or Level 2 battery charging systems, well-designed rate structures could encourage the recharging of vehicle batteries during off-peak hours, typically at night, when the cost of service is lowest. If fast-charging (in less than 15 minutes) systems come into commercial use, the challenge of providing incentives for both consumers and providers of electricity through rate design will increase markedly (see Chapter 4 for a complete discussion of this topic).

In addition, the committee notes the growing controversies over individual privacy and data security that now surround social media. Widespread vehicle recharging does not yet rise to this level of public concern, nor does the committee have any evidence that it will. Nevertheless, privacy and data security issues similar to those that attend the smart grid are likely to apply to the vehicle-charging infrastructure as well. The committee suggests that the GITT remain alert to these. The GITT should be mindful of these and should share best practices in safety codes and emergency response with localities nationwide. And finally, the prospective emergence of fast charging (e.g., Level 3) could also raise issues of public safety.

Wireless charging is a convenient way to charge electric vehicles that increases the flexibility of charging opportunity. The system consists of a low-profile transformer whose primary is on the floor and secondary on the undercarriage of the vehicle. The size of the charger is kept low by using high frequencies, of the order of 100 kHz. This is a relatively new idea that needs development beyond a proof of concept. If successful, it may lead to a next generation in which these transformer primaries are buried in parking spots and can deliver bursts of charge when a vehicle is stopped for a short time. The next step may be dynamic—with the vehicle being continuously or occasionally charged as it drives along a roadway. The convenience of wireless charging has to be balanced against the lack of knowledge of the safety, charge efficiency, and cost of this charging mode.[3] Furthermore, the reliability of such a process and standards have to be established for large-scale implementation. Preliminary economic analysis and standards work on wireless charging are being conducted at the national laboratories, and a 3-year program funded at $4 million per year is being initiated to develop wireless charging, system integration, and technology demonstration.

Recommendation

Greater outreach is needed by the GITT to the state regulatory agencies. The National Association of Regulatory Utility Commissioners could provide an efficient channel for reaching the regulatory community, but contact with individual state commissions will also be needed.

Recommendation 2-9. The grid integration technical team should make a special effort to work with utility regulatory commissions throughout the United States to (1) help identify the best practices in rate regulation that could advance the deployment of plug-in vehicles if widely used and (2) communicate the advantages from these best practices accruing to the public and to state and local officials.

ENVIRONMENTAL IMPLICATIONS OF ALTERNATIVE PATHWAYS

Overview

As noted in the NRC's Phase 1, 2, and 3 reports, it is critical to understand the environmental implications of the full life cycle of alternative fuel pathways, including hydrogen, electricity, biofuels, or other energy source/vehicle combinations being developed that can potentially reduce the consumption of petroleum and reduce greenhouse gas emissions relative to conventional light-duty vehicles (NRC, 2005, 2008, 2010). Researchers conducting life-cycle assessments for passenger transportation would consider the environmental impacts of the materials processing, supply chains, manufacturing, use, and end of life for both the proposed transportation energy sources and the vehicles themselves. Life-cycle assessment, coupled with the fields of industrial ecology and materials flow analysis, can inform policy makers and researchers about the cradle-to-grave impacts of technology decisions (Hendrickson et al., 2006; Brandão et al., 2012; Rogers and Seager, 2009; Graedel and Allenby, 2004; NRC, 2004). By assessing life-cycle impacts, the U.S. DRIVE Partnership can increase the likelihood that

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[3] For example, there may be public concerns about the health and safety effects of electromagnetic radiation.

petroleum reduction and GHG emissions goals are achieved as well as minimize the risk of unforeseen system-wide risks to the environment.

Neither fuel cell nor all-electric vehicles produce tailpipe emissions; the use of these vehicles would thus assist in alleviating local pollution from light-duty vehicles. However, considerable emissions could result from producing the vehicles and storage batteries and producing and delivering fuels, as well as from vehicle disposal. Since publication of the Phase 3 report (NRC, 2010), current research has quantified various environmental aspects of lithium-ion (Li-ion) storage battery production, with several of these works noting the potential of air pollutants and GHGs from battery production to reduce some benefits of battery use in passenger transportation (Dunn et al., 2012; Gaines et al., 2011; Majeau-Bettez et al., 2011; Michalek et al., 2011; Notter et al., 2010; Zackrisson et al., 2010; Hawkins et al., 2012). The Argonne National Laboratory produces a version of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model focused on materials and manufacturing impacts from the vehicle cycle that can also aid in decision making in this area (Argonne National Laboratory, 2011). In addition to the potential impacts of storage battery production, there have been public concerns regarding the large-scale disposal and recycling of storage batteries of various chemistries in a future with widespread adoption of electrified vehicles. The Phase 3 report recommended that the Partnership "should undertake a review of the state of methods and case studies that have been carried out on environmental impacts related to the technologies under development" (NRC, 2010, p. 55). The Partnership agreed and had identified several studies in its response to the report (DOE, 2010). The integration of current and emerging life-cycle assessment research on vehicle, storage battery, and systems materials, and on production for the U.S. DRIVE portfolio of vehicle technologies, as well as the conduct of research to minimize life-cycle environmental impacts, would help to maximize the large potential benefits of electric and fuel cell vehicles.

Electric power generation, hydrogen, and other fuels also generate life-cycle impacts from fuel procurement, production, and infrastructure (Heath and Mann, 2012; Argonne National Laboratory, 2011; Cetinkaya et al., 2012; Lucas et al., 2012; Alvarez et al., 2012). Because the vehicle-use phase accounts for the majority of life-cycle energy use, achieving large life-cycle GHG and air emissions reductions with fuel cell and electrified vehicles is dependent on the production and delivery of low-emissions electricity and hydrogen (Argonne National Laboratory, 2011; Michalek et al., 2011; Elgowainy et al., 2010; Samaras and Meisterling, 2008). Additionally, electricity emissions vary by region, but considerable uncertainty remains in assigning local emissions factors (Weber et al., 2010), and new loads displace disparate marginal generation fuels (Siler-Evans et al., 2012). The comparative analysis of fuel-cycle impacts of electricity, hydrogen, and other fuels used in vehicles is termed "well-to-wheels" or "source-to-wheels" analysis, and well-to-wheels air emissions and GHGs can be estimated with the GREET model (Argonne National Laboratory, 2011).

Due to the inherent uncertainty surrounding emissions from future electricity and hydrogen production and delivery, the Phase 3 report recommended that the links between the systems analysis teams and the technical teams be strengthened and that "technological goals and targets should include consideration of priorities established in systems analysis, and systems analysis should be conducted on emerging technologies identified by the technical teams" (NRC, 2010, p. 55). The Partnership agreed with this recommendation and stated in its response that technical teams and systems analysis teams use the GREET model and systems analysis to track progress and identify technical areas for improvement (DOE, 2010). Progress toward this goal and evidence of appropriate systems analysis were apparent in several presentations delivered by U.S. DRIVE to this committee in 2011 and 2012. The DOE produced a well-to-wheels analysis, shown in Figure 2-1, on the GHG emissions of various technologies for a future midsize vehicle. The uncertainty bands presented demonstrate the impacts of potential vehicle fuel economy and fuel pathways improvements. One potential area of enhancement is for the U.S. DRIVE teams to include vehicle-cycle impacts into such analyses, such as those from the GREET vehicle-cycle model, to understand the full-life-cycle implications, and to use these results as decision-making aides in structuring a balanced R&D portfolio. Regularly updated and publicly available

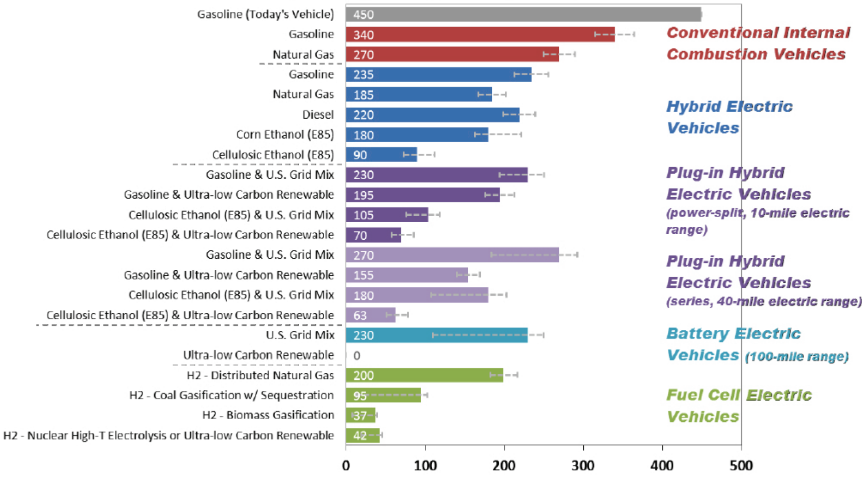

FIGURE 2-1 Department of Energy estimation of well-to-wheels greenhouse gas emissions for a projected state of technologies in 2035-2045 for a future midsize car. NOTE: Ultra-low-carbon renewable electricity includes such sources as wind and solar. The analysis does not include the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning. SOURCE: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf.

charts similar to Figure 2-1 would help stakeholders understand systems impacts and identify potential improvements.

Finally, while Corporate Average Fuel Economy (CAFE) standards affect average GHG emissions from vehicles, the possibility of broader legislation putting a price on economy-wide GHG emissions will affect the economic viability of many future vehicle pathways. U.S. DRIVE can use existing well-to-wheels and vehicle-cycle GHG emissions data to contribute to an understanding of how different levels of GHG pricing could influence economic viability among future vehicle pathways, and use these assessments to inform the broader research portfolio.

The NRC's Phase 3 report recommended that the Partnership should consider incorporating the broader scope of a "cradle-to-grave" analysis rather than a "source (well)-to-wheels" approach in program planning from production to recycling in order to better consider total energy consumption, total emissions, and the total environmental impact of various energy/vehicle pathways and technologies (NRC, 2010). The Partnership agreed (DOE, 2010), and U.S. DRIVE has made progress toward this recommendation, as is evident in several systems analysis presentations and discussions with this committee. However, continued integration of life-cycle impacts and potential improvements into decision making and R&D portfolios would increase the likelihood that the U.S. DRIVE Partnership would achieve GHG goals as well as minimize environmental impacts. U.S. DRIVE's integrated R&D and its portfolio planning would benefit from going beyond a "cradle-to-grave" approach and instead adopting a "cradle-to-cradle" approach, which would optimize processes for limited waste, maximized recycling, and reduced embodied energy of materials used to manufacture critical technology components (McDonough et al., 2003). Other impacts of alternative transportation pathways, such as water use (Harto et al., 2010), remain important areas for integration into U.S. DRIVE systems analysis.

The composition of the electricity grid, which grew and evolved with the economy over the past century, is well outside the scope and control of U.S. DRIVE. However, U.S. DRIVE has the potential to influence the technologies and costs of a future hydrogen production and delivery infrastructure and currently conducts some research on low-carbon hydrogen production.

Recommendations

A life-cycle approach for energy storage batteries can ensure that environmental externalities, including GHGs, conventional pollutants, human health impacts, resource depletion, water use and quality, toxic releases, and others, are minimized for such batteries.

Recommendation 2-10. The U.S. DRIVE Partnership should integrate a life-cycle assessment approach into its research portfolio for energy storage batteries, fuel cell stacks, power electronics, hydrogen fuel tanks, and other advanced vehicle components in order to gain an understanding of the potential environmental impacts of materials processing, supply chains, manufacture, and vehicle use and end of life. U.S. DRIVE should anticipate the potential risk and environmental externalities of battery production and end of life and should research methods to minimize these impacts.

The continued integration of life-cycle impacts and potential improvements into decision making and R&D portfolios would increase the likelihood that the U.S. DRIVE Partnership would achieve GHG goals as well as minimize environmental impacts. Life-cycle analyses are difficult to do comprehensively. They need to adhere to established life-cycle assessment research methods, include sensitivity analysis, be explicit about uncertainties, and be transparent so that all assumptions can be understood and refined.

Recommendation 2-11. The Executive Steering Group as well as the systems analysis teams of the U.S. DRIVE Partnership should identify pathways for fuel cell vehicles and electric vehicles to achieve large life-cycle GHG reductions and structure risk-weighted R&D portfolios to increase the likelihood of achieving these goals at competitive costs. U.S. DRIVE should also update and publicly publish comparisons of per-mile life-cycle GHG emissions across vehicle technologies regularly so that stakeholders can understand all assumptions made, be aware of systems impacts, and identify potential improvements.

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3

Vehicle Subsystems

This chapter discusses the vehicle systems technology areas that the Partnership is addressing in its research and development (R&D) programs, which include the following: (1) advanced combustion, emission control, and fuels for internal combustion engines (ICEs); (2) fuel cells; (3) hydrogen storage onboard a vehicle; (4) electrochemical energy storage or technologies for storing electricity onboard a vehicle; (5) electrical propulsion systems; and (6) materials for reducing the weight of a vehicle. The reader is referred to the presentations from the Partnership to the National Research Council's (NRC's) Committee on Review of the U.S. DRIVE Research Program, Phase 4, on the various technical areas (Appendix D provides a list of the presentations to the committee at its meetings). The presentations can all be found in the project's Public Access File, available through the National Academies Public Access Records Office. Chapter 4 addresses issues associated with hydrogen, electricity, biomass-based fuels, and natural gas.

ADVANCED COMBUSTION ENGINES, EMISSION CONTROL, AND HYDROCARBON FUELS

Introduction and Background

It will take decades to develop and integrate non-internal combustion engine propulsion systems into becoming a significant fraction of the total U.S. mobility fleet. The internal combustion engine will be the dominant power plant for mobility systems for at least the next 20 to 30 years (NRC, 2008, 2010). Consequently it is important to maintain a dedicated effort directed at ICE improvement within the U.S. DRIVE research portfolio.

Furthermore, there is reason for optimism that the drive-cycle-based efficiency of ICEs can be improved, both through engine-based advancements and through hybridization, such that the fuel consumption of engine-powered vehicles can be significantly reduced. Also, the engine has a sophisticated and mature manufacturing basis and is capable of using a range of fuels, from petroleum to liquid-based biofuels to gaseous fuels, derived from a variety of feedstocks. Liquid fuels offer the attractive characteristic of having very high energy per unit of mass and energy per unit of volume. This characteristic facilitates long-range and/or sustained high-power-output vehicle operation. There will be, for many decades, applications for which the ICE-powered vehicle is the best choice.

Life-cycle analyses reported in the literature, such as that shown in Figure 3-1, suggest that total greenhouse gas (GHG) emissions for future high-technology ICE-powered vehicles[1] will be made competitive with non-ICE-powered vehicles on a basis of total GHG life-cycle emissions, while still meeting stringent air quality regulations (Weiss et al., 2000; Bandivadekar et al., 2008). Uncertainty bars in Figure 3-1 denote well-to-tank GHG emissions for electricity generated from coal (upper bound) and natural gas (lower bound). For the well-to-tank GHG emissions from hydrogen fuel cell vehicles (HFCVs; shown as “FCV” in Figure 3-1), it is assumed that the hydrogen fuel is steam-reformed from natural gas at distributed locations and compressed to 10,000 psi.

The advanced combustion and emission control (ACEC) technical team of U.S. DRIVE is the Partnership’s technical interface with the research community’s activities in advanced combustion and emission control. The goals, technical targets, and program structure of the ACEC technical team build on those from the FreedomCAR and Fuel Partnership, which in turn built on the goals and targets from the Partnership for a New Generation of Vehicles (PNGV). For the FreedomCAR program, the advanced combustion and emission control targets and results were as follows:[2]

- Peak engine brake thermal efficiency (BTE) of 45 percent
  —This BTE was demonstrated with a light-duty diesel engine and an H_2-fueled ICE.
- Oxides of nitrogen (NO_x) and particulate matter (PM) emissions for light-duty diesel engines at Tier 2 Bin 5 (T2B5) standards
  — Twelve vehicle models that met this target were commercially available in the 2012 model year (MY).

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[1] Hybrid electric vehicles and plug-in hybrid electric vehicles are included in this classification because the engine still plays a major role as the energy converter between the fuel energy and work delivered to the wheels.

[2] R. Peterson, General Motors, and K. Howden, Department of Energy, “Advanced Combustion and Emission Control Technical Team,” presentation to the committee, January 26, 2012, Washington, D.C.

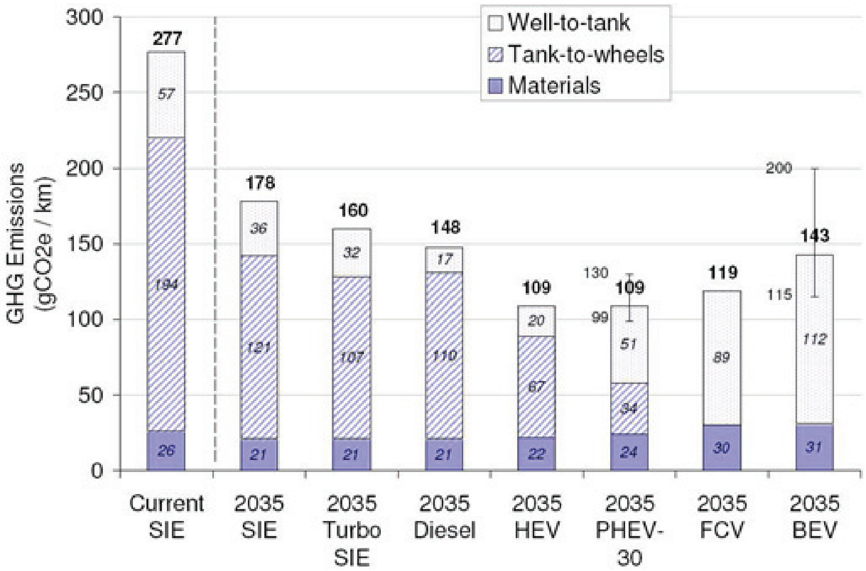

FIGURE 3-1 Predicted comparative total greenhouse gas emissions for current spark ignition engines (SIEs) and potential 2035 propulsion systems. NOTE: Acronyms are defined in Appendix E. SOURCE: Bandivadekar et al. (2008).

- Power-train cost of $30/kW
  - — This cost target guidance and status are currently under evaluation by U.S. DRIVE.

To push past the targets of the FreedomCAR and Fuel Partnership, the U.S. DRIVE Partnership addressed three engine technology pathways: (1) hybrid optimized (low-level power density), (2) naturally aspirated (mid-level power density), and (3) downsized and boosted (high-level power density); it identified engine efficiency metrics at three load conditions: peak efficiency; 2-bar brake mean effective pressure (BMEP)—2,000 revolutions per minute (rpm); and 20 percent of peak load—2,000 rpm.

The specific 2020 stretch targets were set relative to 2010 MY engines for each technology pathway. Table 3-1 shows a compilation of these targets for each engine technology pathway for each of the three metric conditions. Standard fuels, either gasoline or diesel, are considered in specifying the performance metrics.

For each of the three pathways being pursued to achieve the targets shown in Table 3-1, the fundamental approach and issues being addressed are these:

1. High-efficiency combustion with low engine-out emissions
   - — Low-temperature combustion (LTC)

TABLE 3-1 Advanced Combustion and Emission Control Efficiency Baselines (2010) and Stretch Targets (2020)

		2010 Baselines				2020 Stretch Targets		
Technology Pathway	Fuel	Peak Efficiency (%)	Efficiency[a] @ 2-bar BMEP and 2,000 rpm (%)	Efficiency[a] @ 20% of Peak Load and 2,000 rpm (%)	Peak Load[b] at 2,000 rpm	Peak Efficiency (%)[c]	Efficiency[c] @ 2-bar BMEP and 2,000 rpm (%)	Efficiency[c] @ 20% of Peak Load and 2,000 rpm (%)
Hybrid application	Gasoline	38	25	25	9.3	46	30	30
Naturally aspirated	Gasoline	36	23	23	10.7	43	28	28
Downsized boosted	Gasoline	37	22	29	19	44	27	35
	Diesel	40	26	32	21	48	31	38

[a] Entries in percent brake thermal efficiency (BTE).

[b] Entries in bar of brake mean effective pressure (BMEP).

[c] Entries in percent BTE that are equal to 1.2 times the corresponding baseline BTE.

SOURCE: R. Peterson, General Motors, and K. Howden, Department of Energy, "Advanced Combustion and Emission Control Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

  - — Dilute spark-ignited combustion
  - — Clean diesel
2. Improved efficiency with waste energy recovery
  - — Solid-state and mechanical approaches
  - — Improved air handling and lubricants
3. Efficient aftertreatment systems that reduce the energy penalty and meet emissions regulations
  - — NO_x, PM, hydrocarbons (HC), and carbon monoxide (CO)

At first glance the above list of technology pathways appears to focus on development-type issues that would best be addressed by industry as part of product development. However, the barriers to achieving the targets given above are fundamental understandings of the controlling phenomena for each pathway, and this is the focus of the U.S. DRIVE activities. The optimization of the interaction among the following is very complicated: the ambient conditions; the details of the gas exchange processes (intake and exhaust processes, exhaust gas recirculation [EGR], boost, intercooling, manifold geometry, valving events, etc.); the in-cylinder processes (injection characteristics, in-cylinder flow, combustion chamber geometry, fuel chemistry, etc.); and the exhaust-gas aftertreatment system (PM traps, NO_x reduction systems, CO and HC oxidation systems, etc.) for minimum fuel consumption while meeting emissions standards. To address these challenges, industry uses analysis-led design, in which computational fluid dynamics (CFD) is used to predict the optimum combinations of power-train system control parameters for each engine operating regime.

This process is only as good as the accuracy and fidelity of the CFD programs being used. Consequently, the lack of a detailed fundamental understanding of the various thermo-fluid-chemical processes and their incorporation into CFD submodels is a barrier to further engine system optimization. Certain aspects of the challenges that industry must deal with are not understood at this time: for example, there is no accepted explanation for how lubricating oil is involved in the particulate formation processes within the engine cylinder. This is a relevant example of the importance of a lack of fundamental understanding, because higher-efficiency engines will rely on controlled air-fuel heterogeneity within the cylinder, which can lead to significant nanoparticle formation. Lack of understanding of the detailed processes occurring in the combustion chamber, like the particulate formation, subsequently impedes the optimization of engine performance through simulation.

The engine combustion and emission research community is collaborating with industry to address these fundamental issues through experiment and simulation. To best duplicate the conditions in which to probe a deeper fundamental understanding of these phenomena, researchers perform experiments and simulations in representative engine geometries under real operating conditions.

The primary framework through which the U.S. DRIVE ACEC technical team engages with research activities on combustion and emission controls is through the U.S. Department of Energy's (DOE's) Office of Vehicle Technologies Program (VTP). This office supports fundamental research in combustion, energy recovery, and aftertreatment performance. Within these programs there is participation from industry, DOE national laboratories (Argonne National Laboratory [ANL], the Sandia National Laboratories [SNL] Combustion Research Facility, Oak Ridge National Laboratory [ORNL], Pacific Northwest National Laboratory [PNNL], Lawrence Livermore National Laboratory [LLNL], and Los Alamos National Laboratory [LANL]), and universities.

DOE's vision of the collaborative activities between national laboratories, universities, and industry is a progression from fundamental to applied research to technology maturation and deployment. Fundamental R&D is the focus of activities at the following:

- Sandia National Laboratories
  - —E.g., Combustion Research Facility (lean-burn, LTC, advanced direct injection)
- Pacific Northwest National Laboratory
  - —E.g., catalyst characterization (NO_x and PM control)
- Argonne National Laboratory
  - —E.g., x-ray fuel spray characterization
- Lawrence Livermore National Laboratory
  - —E.g., chemical kinetics models (LTC and emissions)
- Los Alamos National Laboratory
  - —E.g., CFD modeling of combustion (KIVA code development)
- Universities
  - —Complementary research

The fundamental to applied bridging R&D is performed at the following:

- Oak Ridge National Laboratory
  - —E.g., experiments and simulation of engines and emission control systems (bench-scale to fully integrated systems)
- Argonne National Laboratory
  - —E.g., H_2-fueled ICE, fuel-injector design

Finally, competitively awarded cost-shared industry R&D is done by the following:

- Automotive and engine companies and suppliers
  - —E.g., engine systems and enabling technologies (sensors, variable valve actuation, waste heat recovery)

The advanced combustion and emissions control program is well managed. The organizational structure of its activities involves memoranda of understanding between companies and government laboratories. It is usual for individual projects to include one or more of the national laboratories, a university, and an industrial partner. To ensure relevance, industry cofunding or matching is often required. In addition to the regular research meetings within a specific project, two formal research reviews are held each year, one at the Sandia Combustion Research Facility in Livermore, California, and one at the U.S. Council for Automotive Research (USCAR) in Southfield, Michigan. The researchers also participate in the DOE Annual Merit Review.

Additional avenues for technical interchange are promoted through CLEERS (Crosscut Lean Exhaust Emission Reduction Simulation) and the Engine Combustion Network (ECN).

CLEERS sponsors monthly teleconferences and an annual workshop to promote the development of improved computational tools for simulating realistic full-system performance of lean-burn diesel/gasoline engine and associated emission control systems. This activity helps in the development of emission control models that are integrated into vehicle simulations for drive-cycle analysis within the vehicle systems and analysis technical team (VSATT).

The ECN supports a website and teleconferences to share and leverage research between experimenters and modelers on direct-injection fuel sprays and combustion.

Overview of Technologies Being Investigated

To implement new combustion strategies, effective exhaust-gas energy recovery, and aftertreatment systems that promote efficient engine operation, the air handling, combustion, and exhaust subsystem must be optimized as a system. Such optimization requires advanced computational fluid dynamics. It is now common that the design of a new power-train system is led by CFD. To extract increasingly better performance from the power train requires more accurate and detailed computational models. These models are developed through the coupling of fundamental experiments and computational submodel development. This is the interface at which the U.S. DRIVE effort is focused.

In the area of high-efficiency combustion, the emphasis continues to be on low-temperature combustion. LTC is in essence controlled knock, and it relies on the auto-ignition chemistry of the fuel. Regardless of the fuel, the underlying approach to achieving acceptable LTC is the same. One wants to get the fuel vaporized and partially mixed with the cylinder gases such that when the auto-ignition chemistry reaches the point of ignition, the energy release is volumetric. Furthermore there needs to be sufficient inhomogeneity of the mixture within the combustion chamber that the entire mixture does not auto-ignite all at once, which would lead to excessive rates of pressure rise. This inhomogeneity can be in temperature, air-fuel ratio, or degree to which the local mixtures have kinetically traversed their auto-ignition pathway. If this is achieved, the engine efficiency is higher and the in-cylinder emissions are very low. The approach taken to control LTC will be dependent on the fuel type—gasoline-like, diesel-like, or dual fuels—and the load demanded of the engine. Since the NRC (2010) Phase 3 review of the FreedomCAR and Fuel Partnership carried out in 2009, five new combustion projects have been started to address these challenges.

Regardless of how efficient the engine is, there will always be some usable energy in the exhaust that leaves the cylinder. As the engine efficiency gets higher, the usable energy in the exhaust gets smaller. Thermodynamically, it is known that as the portion of recoverable energy in the exhaust decreases, the efficiency of an exhaust-gas energy recovery system also decreases. However, in the quest to maximize engine efficiency, gains can still be made by the inclusion of exhaust-gas energy recovery systems. This imposes challenging constraints on the cost-benefit assessment of implementing energy recovery systems in the exhaust, and on maintaining a highly efficient exhaust-gas aftertreatment system.

The fundamental research being pursued on exhaust-gas energy recovery within the ACEC technical team is to develop energy recovery systems that maximize the conversion of usable exhaust energy in ways that are economically viable. Research programs addressing exhaust-gas energy recovery involve electricity generation with thermoelectrics, as well as more efficient turbomachinery and air handling. In addition, work is being supported on advanced lubricants, improved friction management, and materials for higher operating pressures and temperatures.

Within the aftertreatment research programs, there are activities on developing efficient catalysts that operate at lower exhaust temperature, improved NO_x and PM aftertreatment systems, reducing the platinum group metal (PGM) requirement for the aftertreatment systems, and combining multiple aftertreatment systems into a single unit.

The predictive capabilities of the current CFD programs are good. The simulation code used most widely at this time is KIVA III, developed by DOE. KIVA is an open-source-code program, which allows researchers to incorporate new understanding directly into the code for any aspect of the thermophysical processes occurring within the engine. For example, improved kinetic schemes for different fuel types or new submodels that more accurately represent liquid fuel-combustion chamber surface interactions can be implemented into the code and then exercised for more detailed predictions of combustion results. However, KIVA III is more than 12 years old and lacks important, modern numerical technologies such as parallel computing and using an object-oriented structure. Having an up-to-date, open-source CFD program for researchers to use is a critical aspect of achieving the improvement potential of the ICE and aftertreatment power trains.

The DOE is supporting work on a new version of the code, KIVA IV. To date the code has not been widely adopted. Discussions of committee members[3] with academic users led to a list of possible reasons for the code not being widely adopted:

- A code with KIVA IV's level of physics and geometry (engines) needs to be modular and needs to have a data structure that is object-oriented.
- The current effort allocated does not appear to provide the level of development support required for doing an acceptable job—an increased effort was suggested by academic users and submodel developers.
- Code development for KIVA needs to be strongly tied to the activities of its "customers," which are predominantly the universities where the advanced submodels are being developed and implemented.
- Intellectual property (IP) issues associated with the code and submodels may be jeopardizing the open-source designation. If this key element is lost, the university following could disappear, which seems to be happening.

Perhaps if a more active interface could be established between researchers working on the code development, university and research groups developing submodels, and industry partners, who will be the ultimate users of the code, the adaptation of the new code could be expedited.

The energy companies continue to be engaged, and the program of Fuels for Advanced Combustion Engines (FACE), organized under the Coordinating Research Council (CRC), is supplying an important database for quantifying the impact of fuel characteristics on engine emission processes and alternative combustion process facilitation.

In response to questions from the committee, U.S. DRIVE Partnership officials commented that natural gas is not included in the Partnership's technical scope. The committee believes that in light of the increased supply of natural gas and the high interest in using it to displace petroleum, an assessment should be made of whether natural gas is in any way an enabler for achieving U.S. DRIVE goals. For example, does natural gas facilitate the advanced combustion modes under investigation within U.S. DRIVE?

The ACEC technical team's responses to the recommendation of the previous review were good. The team is continuing to look for opportunities to enhance collaboration and has a program in KIVA code development. As discussed above, the committee believes that the KIVA code development effort could be improved. The ACEC technical team is making more use of the vehicle simulation that is being developed by the VSATT, and although it is not engaged in biofuels research, the team is aware of activities in the field. Also, the approach being

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[3] In particular, David Foster, committee member, had discussions with academic users.

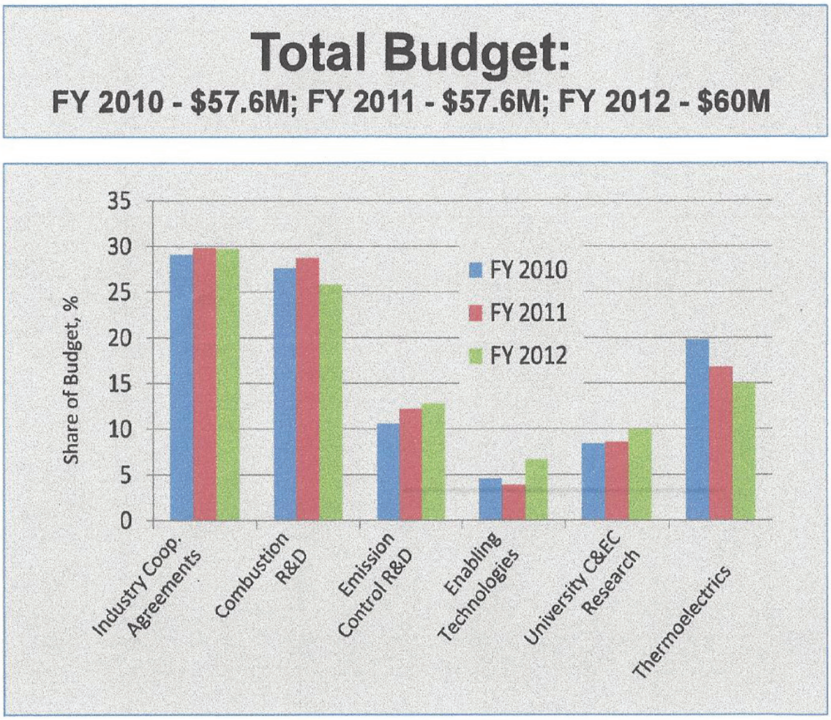

FIGURE 3-2 Department of Energy advanced combustion engine research and development (R&D) funding—FY 2010 to FY 2012. SOURCE: R. Peterson, General Motors, and K. Howden, Department of Energy, "Advanced Combustion and Emission Control Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

taken within the ACEC technical team's programs in developing kinetic models for combustion process simulation is compatible with the inclusion of compositional changes that could occur to the fuel when biomass-derived compounds are blended with the fuel.

Funding

Even though the U.S. DRIVE Partnership's ACEC technical team does not exercise control over a budget, it did offer to the committee an overview of the DOE funding within the advanced combustion and emission control programs for FY 2010 through FY 2012 (see Figure 3-2).

Within the scope of the U.S. DRIVE goals, the work allocation for the continued development of the ICE and vehicle electrification seems appropriate.

Accomplishments

This section presents a summary of accomplishments related to R&D activities in the areas of advanced combustion, emission control, and fuels for internal combustion engines.[4]

Low-temperature combustion has proven to be an effective means of improving closed-cycle efficiency and reducing the formation of NO_x and particulates. By reducing the formation of NO_x, both the cost and the complexity of additional aftertreatment can be reduced. The benefits of LTC are known, and include dramatic reductions in the formation of NO_x. However, controlling the in-cylinder processes leading to successful LTC operation is a challenge. The ACEC technical team has demonstrated a number of successes both in the control of LTC and in expanding its operational range within the engine duty cycle.

One example of this success is a project at ANL where researchers were able to use 87 research octane number (RON) gasoline in a 1.9-liter turbocharged engine while retaining a full load range and diesel levels of efficiency with substantially reduced NO_x.

The Sandia National Laboratories achieved indicated thermal efficiencies as high as 48 percent by using partial fuel stratification in a boosted homogeneous charge compression ignition (HCCI) engine.

The ORNL has a project using E85 (a mixture of 85 percent ethanol and 15 percent gasoline) in a spark-assisted HCCI engine. A 17 percent increase in indicated thermal efficiency was achieved as compared to that of gasoline and over a wide range of loads.

The use of two fuels, while adding some complexities and costs, also adds to the capabilities of controlling combustion and emissions. Reactivity controlled compression ignition (RCCI) engines involve the in-cylinder blending of two fuels with differing reactivity in order to tailor the reactivity of the fuel charge. Researchers at ORNL and the University of Wisconsin have used a diesel/gasoline multicylinder engine RCCI to demonstrate efficiencies up to 5 percent greater than diesel efficiencies. To better understand how dual fuels provide the benefits, fuel mixing and RCCI combustion were imaged from inside an optical engine by researchers at SNL and the University of Wisconsin.

In other combustion research approaches, researchers from ANL, SNL, and the Ford Motor Company, using advanced direct injection of hydrogen, were able to achieve 45.5 percent peak brake thermal efficiency of a hydrogen-fueled ICE. Further, it is expected that minimal exhaust aftertreatment will be required to meet stringent emission goals. The researchers were also able to demonstrate a part-load efficiency of 31 percent while meeting T2B5 emissions standards.

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[4] A full summary of accomplishments can be found in *U.S. DRIVE Highlights of Technical Accomplishments: 2011*, available at http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2011_usdrive_accomplishments_rpt.pdf.

Detailed CFD and supporting experimental activities are critical to achieving more efficient combustion modes. The Lawrence Livermore National Laboratory has developed new approaches to computing fuel combustion chemistry using desktop-scale workstations, containing graphical processing units (GPUs) in addition to conventional central processing units (CPUs), that result in about an order-of-magnitude decrease in computation time.

Additional accomplishments relate to improved understanding of engine lubrication, spray and combustion modeling, EGR control, and exhaust energy recovery. The ORNL, working with Cummins, Inc., has developed a fiber-optic probe with laser-induced fluorescence to provide an accurate measurement of fuel dilution in engine oil. This technology has already been licensed to industry.

Researchers at ANL, the University of Illinois at Chicago, and Caterpillar have developed a new spray model for diesel engines that accounts for effects such as cavitation and turbulence in addition to aerodynamic breakup.

There are several other ICE-related projects that have added to industry's ability to produce more efficient engines with lower emissions. Among those, SNL established the ECN, an international, multi-institutional collaboration with goals of improving the understanding of spray nozzles and increasing the capability of developing predictive spray models. Also, ORNL, the University of Michigan, and Ford Motor Company have provided a new understanding of EGR fouling mechanisms that can lead to improved EGR heat exchanger designs.[5]

Other important projects include collaboration between Ford Motor Company, Wayne State University, and ConceptsNREC to improve turbocharger design so as to improve engine efficiency while increasing rated power. Finally, through DOE working with Ford Motor Company, an improved aftertreatment system to minimize NO_x emissions with selective catalytic reduction (SCR) was developed.

Conclusions

The ACEC technical team is making good progress. It is doing a good job at maintaining a close and constructive working relationship with the stakeholders within the vehicle and energy community. It is critical for the technical team to maintain this collaboration and to look for ways to make it even stronger.

The major barrier to implementing advanced combustion, aftertreatment, and fuel technologies continues to be an insufficient knowledge base. For example, the understanding necessary to control low-temperature combustion over a large portion of the engine map is a fundamental area appropriate for federal support. Topic-specific understanding is critical to continued improvement of the ICE power train; also critical is understanding of the system-level interactions between

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[5] Further details on this work can be found at http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2011/tuesday/presentations/deer11_styles.pdf.

the energy carrier, the energy release process, and the final emission cleanup.[6] Continued close collaboration between DOE and industry is necessary to allow newly developed understandings to transition into the industrial laboratories and to enable the identification of new areas where enhanced understanding will be most beneficial. Even though the thrust of current activities within the U.S. DRIVE Partnership is to develop the technologies necessary to meet performance targets, being able to implement the technologies into vehicles that are affordable will ultimately determine their success.

The ACEC technical team is a well-managed activity and should be recognized for its accomplishments. However, the committee does have two recommendations that it believes will make the program stronger and more complete.

Recommendations

Because computational fluid dynamics plays an indispensable role in future engine-power train system development, having a robust, modern code in which researchers can integrate and exercise improved submodels is critical. The U.S. DRIVE Partnership is working on the next generation of KIVA, but KIVA IV may not be widely adopted by the research community.

Recommendation 3-1. The DOE should undertake a larger effort on the next generation of KIVA in order to be successful in facilitating such a resource. There should be a more formal collaboration established among the industry stakeholders, university stakeholders, and the DOE researchers doing the development work for KIVA IV. Efforts should be made to implement a modular and object-oriented structure to the code that is most useful to the ultimate stakeholders.

Domestic natural gas reserves and production are growing rapidly, providing for possible future use in ICE vehicles.

Recommendation 3-2. U.S. DRIVE should make an assessment of whether natural gas can be an enabler for achieving the advanced combustion modes currently being pursued in its research portfolio.

FUEL CELLS

Fuel cell vehicles, under development globally, are based on a technology that can ultimately result in a zero-emissions and fossil-fuel-free option for transportation applications, and can help meet the vision of the U.S. DRIVE Partnership. Elegantly simple in concept, it has been a costly and daunting task to develop

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[6] Hybrid electric and even plug-in hybrid electric power trains are included in the general classification of power train.

fuel cell technology for vehicular applications. This has been partly due to the expectation that at the time of the rollout of such vehicles, the new technology would mimic current ICE vehicle operational standards and turn-key performance under all conditions at a competitive cost. The challenge has also partly rested with the fact that fuel cell power plant and ancillary subsystems are unrelated to any power-train technology previously used in conventional vehicular applications. In development for well over two decades, the vehicle original equipment manufacturers (OEMs) have now engineered, built, and tested fuel-cell-powered prototype vehicles, which appear to have met many consumer expectations with respect to vehicle performance. Automotive OEMs, with the assistance of suppliers and end users in the United States, have now begun to generate statistically significant on-road performance data leading to further confidence in the technology, engineering refinements, and identification of areas requiring further development. If the hydrogen fueling infrastructure, currently in its infancy, can evolve based on renewable hydrogen generation processes, there is a good chance that the vision of the U.S. DRIVE Partnership and its predecessor organizations will be achieved. Regardless of the source of the hydrogen, the development of a production and distribution infrastructure is clearly essential for the possible success of widespread hydrogen fuel cell vehicles (see Chapter 4).

The DOE's primary role in fuel cell R&D is to facilitate the advancement of precompetitive technology that is considered longer term and high risk. These are projects that, if successful, will provide the OEMs with "next-generation" technical options. Assessment of the approximately 300 projects currently funded by DOE indicates that approximately 65 percent fall within the technology readiness levels (TRLs) of 2 and 4—that is, basic research efforts as well as activities related to analytical and experimental proof of concepts.[7] Only a small percentage (7 percent) of funding is allocated to nearer-term initiatives (TRL 7).

The lifetime of the fuel cell stack is still a limiting factor. The current stack life is approximately half of the targeted lifetime as set forth by the Partnership. The 5,000-hour target required with minimal degradation has still not been achieved, as reported by the National Renewable Energy Laboratory (NREL) in on-road vehicle tests (Wipke et al., 2012); however, proton exchange membrane (PEM)-based bus stack lifetimes have exceeded 10,000 hours with similar technology. Advancements in systems engineering focusing on stack operation will also play a role in meeting the lifetime targets. Reports by NREL on fuel cell performance in on-road vehicle tests, based on 2009 vehicle technology, indicate that significant advancements have been achieved (Wipke et al., 2012).

Recent results presented at the 2011 and 2012 DOE Annual Merit Review meetings have indicated that the key issues impacting fuel cell performance are under investigation at the national laboratories, within academia, and in indus-

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[7] S. Satyapal, Department of Energy, "Fuel Cell Technologies Overview," presentation to the committee, December 5, 2011, Washington, D.C.

try.[8] Degradation mechanisms and performance limitations of the fuel cell power module are now the focus of such efforts, leading to a better understanding of the primary life-limiting issues. Reports from the Annual Merit Review over the past 3 years continue to show that laboratory tests of single cells have in many cases surpassed the program lifetime target (Debe, 2011, 2012), yet the laboratory and on-road test results are still in need of addressing operability and performance issues. As a result, technology and stack operating modes tested in the laboratory and those encountered during on-road vehicle tests are now being coordinated. The conclusions and outcomes of such efforts are essential to the delineation of the technical issues that need to be addressed when moving from the laboratory to real-world applications.

Assessment of the Program and Key Achievements

The fuel cell activities and resultant achievements can be grouped into three categories: (1) on-road vehicle performance, (2) longer-term R&D, and (3) near-term programs to support the secondary activities, including cost and engineering modeling, as well as programs focused on the adoption of the technology. All three areas have progressed at various paces since the Phase 3 NRC (2010) review.

Fuel Cell Vehicle Performance

On-road tests of hundreds of vehicles have been completed since the NRC (2010) Phase 3 review. Although it is difficult to state conclusively the magnitude and extent of the progress, such results are impressive, as reported by NREL (see Figure 3-3). It is significant that the results of the on-road field vehicle demonstration programs were generated with vehicles using 2009 or earlier technology. Additional progress has been made since then by the OEMs. The past and current status of selected metrics, including power density (W/l) and specific power (W/kg), cost, durability, start times at –20°C, and energy efficiency at 25 percent rated power are presented in the spider chart in Figure 3-3. It is clearly evident that all of the metrics have met or are approaching the 2017 targets except for cost and durability. Significant progress has been made in the past 8 years.

Long-Term R&D

Long-term programs account for 65 percent of the fuel cell activities, ranging from proof of concept to applied engineering efforts. The topics addressed in this category are for the most part continuation and follow-on programs of prior efforts. This continuity is critical, as the programs that have survived the go/no-go decisions are the ones deemed to have the most significant potential.

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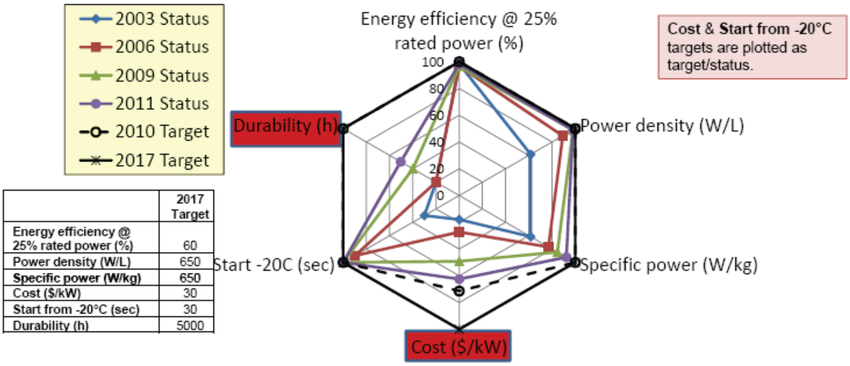
[8] See DOE's Annual Merit Reviews, at http://www.annualmeritreview.energy.gov/.



	2017 Target
Energy efficiency @ 25% rated power (%)	60
Power density (W/L)	650
Specific power (W/kg)	650
Cost ($/kW)	30
Start from -20°C (sec)	30
Durability (h)	5000

FIGURE 3-3 Spider chart of fuel cell performance results versus targets for various years. SOURCE: C. Gittleman, General Motors, and K. Epping Martin, Department of Energy, "Fuel Cell Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

There are new programs, but the number and magnitude have been limited. Since the Phase 3 review, five proposed efforts have been funded. New research efforts have originated through other offices besides the Office of Energy Efficiency and Renewable Energy (EERE), including the Office of Basic Energy Sciences (BES) and Small Business Innovation Research (SBIR) programs.

The accomplishments and progress considered significant in the past few years focus on the two main barriers, durability and cost. With respect to the barriers, the primary emphasis has been on the membrane electrode assembly (MEA), consisting of catalysts and membranes sandwiched between two carbon-based gas diffusion layers. The assembly is then placed between two plates, resulting in anode and cathode compartments (the cell). The cells are then stacked on one another until the desired voltage-current specification is met. Catalysts, predominately platinum group-based, are formulated with binders and/or ionomeric materials (proton conducting polymer) and fabricated into an electrode layer, which is applied to either the membrane or gas diffusion media. The majority of the currently funded efforts are on performance and durability aspects of carbon-free supported catalysts, non-precious metal catalysts, the quantity of catalysts required per cell, as well as on lower-cost, durable membranes. If success is achieved in any one of the above areas, the attractiveness of the fuel cell from a cost and durability perspective would be greatly enhanced. As noted in its recommendations, the committee believes that these activities should be increased in scope and that the budget should be adjusted to reflect the change.

Recent progress at the laboratory level has been promising, but it in no way implies the successful viability or the adoption of the advancements in fuel cell stacks when used in vehicles. With that said, recent work reported by Argonne

National Laboratory (Myers et al., 2011, 2012) at the 2011 and 2012 DOE Annual Merit Review meetings on determining the fundamental degradation mechanisms of MEAs has provided invaluable insight into the science of the failure modes of the catalysts and membranes. A number of other efforts to change catalyst supports, the architecture of the catalyst layers, and the work to develop non-precious metal catalysts will benefit from the findings of this effort. As the MEA is a complex "system," changes in any one component will impact the functionality and performance characteristics of the entire assembly. As a result, advancements and scientific findings in each area must be thoroughly communicated, including to the industrial partners who will ultimately fabricate the MEA in high volumes. An assessment of the interrelationships of the fuel cell technical team with associated organizations indicates that the dissemination of information is taking place at the appropriate level on the membrane and electrode topics.

The catalyst development efforts have resided mainly at the national laboratories, where steady progress has been made in enhancing the catalytic activity as a function of the amount of catalyst required to support the reactions. The development of carbon-free supported catalysts is also underway. Durability, stability, and poisoning issues remain, but the results are promising, and as such these activities are essential if the ultimate targets are to be met. For example, at the national laboratories, fundamental electrochemical-catalyst modeling to predict performance-cost benefits is underway, as are activities to improve the understanding of the platinum core shell catalysts and the promising $Pt_3Ni(111)$ alloys, among others, and the impact of processing and operating conditions on them. Non-precious metal catalysts are also being investigated. Industrial organizations, predominately the ones that will eventually be part of the backbone of the supply chain, are engaged, with 3M being an example. The 3M activity on the nanostructured thin film (NSTF) electrode is showing good progress, not only from a catalysis perspective but also from the electrode layer architecture and the impact of water dynamics in a functioning MEA. The contributions of 3M with respect to the effect of gas diffusion media on performance offer another example of the interrelationships of the different layers within the MEA.

Because catalysts are at the heart of the electrochemical process and are a major cost component of the stack, research activity in this area is considered significant and appropriate and should be continued. It should be noted that selected aspects of catalyst and electrode technology used in fuel cells may provide guidance and direction in other electrochemical processes as well (e.g., batteries).

Proton exchange membranes are composed of complex polymers that must be able to transport protons efficiently with minimal resistance and at the same time exhibit acceptable mechanical strength and low gas permeability. They must be low cost and be able to be easily manufactured. The polymer/membrane development is a long and costly process. The DOE is aware of this and has been appropriately supporting new membrane development for a number of years in academia and national laboratories and within industrial organizations.

TABLE 3-2 Fuel Cell Stack and Stack Component Progress in Relation to the U.S. DRIVE 2010 and 2017 Targets

	2010 Target	2011 Status	2017 Target
Fuel cell stack durability (hr)[a]	5,000	3,700	5,000
Fuel cell stack cost ($/kW$_e$)[b]	25	22	15
Membrane electrode assembly (MEA) cost ($/kW$_e$)[b]	14	13	9
MEA total Pt group metal total content (g/kW)	0.15	0.19[c]	0.125
Non-Pt catalyst activity per volume of supported catalyst (A/cm^3 @ 800 mV$_{\text{IR-free}}$)	130	127[d]	300
Bipolar plate cost ($/kW)[b]	5	5	3

[a] Projected time to 10 percent voltage degradation from the technology validation activity.

[b] Cost status is from 2011 DTI study; costs are projected to high-volume production (500,000 stacks per year). Available at http://www.hydrogen.energy.gov/pdfs/review11/fc018_james_2011_o.pdf.

[c] M. Debe, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Merit Review Proceedings, May, 2011. Available at http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf.

[d] P. Zelenay, H. Chung, C. Johnston, N. Mack, M. Nelson, P. Turner, and G. Wu. 2011. *FY 2010 Annual Progress Report for the DOE Hydrogen Program.* DOE/GO-102011-3178. U.S. Department of Energy, February, p. 816.

SOURCE: C. Gittleman, General Motors, and K. Epping Martin, Department of Energy, "Fuel Cell Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

The focus has appropriately been on membranes that can operate with reduced hydration requirements and/or higher operating temperatures and at the same time exhibit higher conductivities. The committee sees less value in supporting membrane-based subsystem development—for example, in enthalpy exchange processes—as this is more of an engineering initiative and not deemed long-term, high-risk research. The financial resources used to fund the near-term engineering initiatives should be reallocated to topic areas that impact the durability and/or cost issues.

Table 3-2 summarizes the fuel cell stack and stack component progress against the 2010 and 2017 targets.

Near-Term Supporting Efforts

The DOE and the U.S. DRIVE Partnership have developed additional mechanisms by which the key fuel cell issues are addressed. Although the programs highlighted above are selected through the DOE solicitation-proposal process, working groups have been formed to facilitate better communication among the stakeholders and are also being asked to focus on the most critical needs (e.g., durability, modeling, and catalysis). The teams are led by national laboratory representatives and involve catalyst and membrane suppliers as well as fuel cell companies, vehicle OEMs, and other participants. As articulated by the fuel cell technical team during the review process, the primary objectives are to (1) promote sharing in the learning, (2) prevent duplication of effort, and (3) disseminate the findings to the fuel cell community. The committee sees this activity as a valuable means to maximize progress and learning through such a coordinated effort. Cooperation among the team members on critical precompetitive research topics will accelerate and facilitate solutions for the entire industry.

The past three NRC reviews of this program have expressed concerns that the cost assessments as reported are difficult to endorse fully as the technology was still evolving, the supply chain immature, and the technology used by the OEMs unknown to the assessment committee. The Phase 3 report (NRC, 2010) noted that even with these uncertainties, the estimated costs for the fuel cell system (for 500,000 per year production) represented a reference point from which to measure cost-reduction progress. As the $30/kW target is still quite challenging, the technical development and cost-reduction efforts currently underway must be appropriately funded. Figure 3-4 presents the reported cost estimates for the fuel cell system for the last 5 years. The most recent estimate is also included (2011).

Although it is difficult to validate the absolute value of the reduction in system costs, the trend is quite apparent. New manufacturing initiatives will further impart greater certainty in the numbers, as will commitments to the OEMs by the

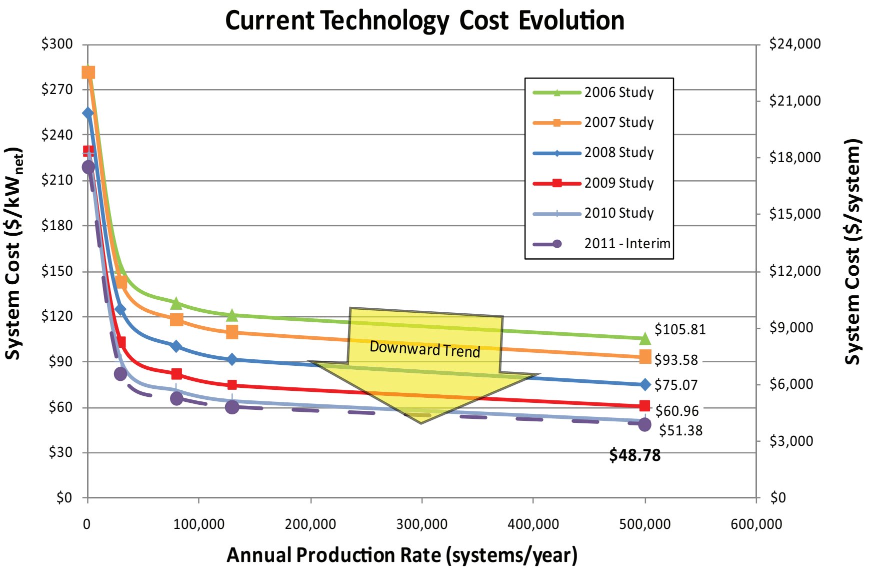


FIGURE 3-4 Cost estimate on a dollars per kilowatt ($/kW) basis for the fuel cell system, not including onboard hydrogen storage. SOURCE: C. Gittleman, General Motors, and K. Epping Martin, Department of Energy, "Fuel Cell Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

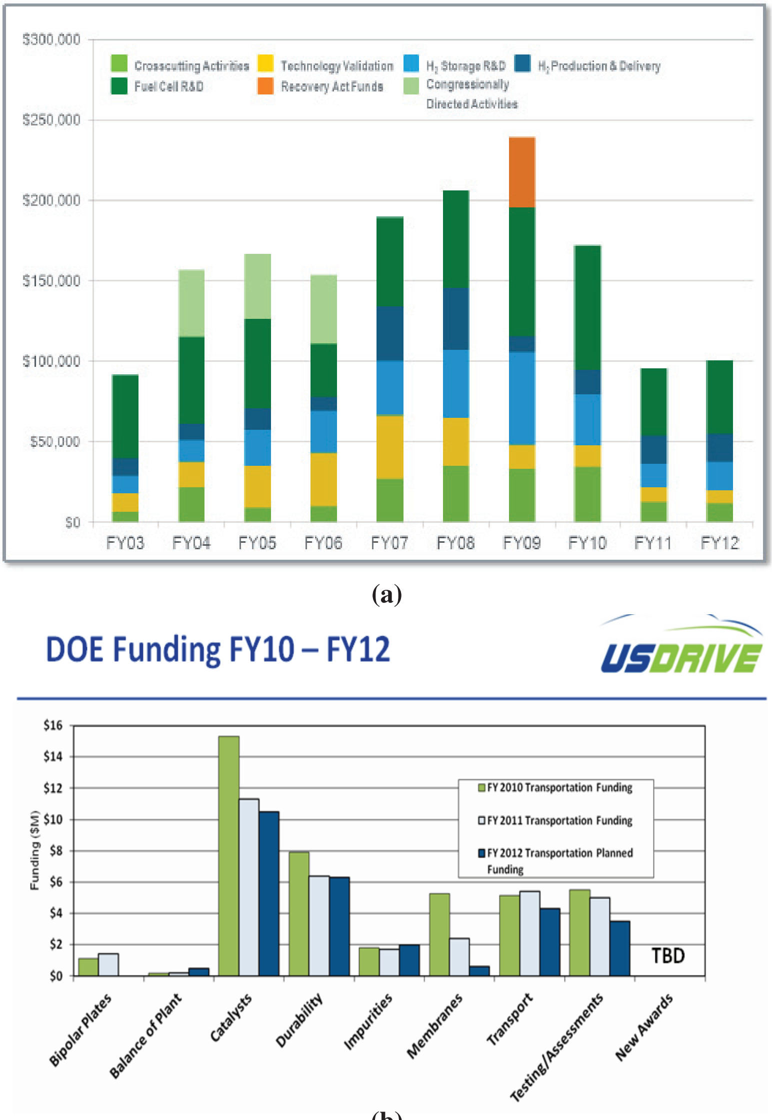
supply chain. As technology development efforts continue to progress, it is not possible to know at this time if there will be a significant impact on cost. High-volume vehicle production will not result in economies of scale with respect to the price of platinum. Platinum costs can be mitigated by recycling strategies, but the stack lifetime issue will impact maintenance and stack replacement costs until such time as durability issues are resolved. As it is not apparent that lifetime targets will be met any time soon, DOE should consider including, as part of its modeling efforts, not only the original bill of materials but also a realistic assessment of component replacement costs for the near term.

In addition to component costs, manufacturing processes must be efficient in leading to a high yield of finished goods. The membrane electrode assembly, the heart of the power generation unit, is a complicated and costly five-layer package composed of membranes and catalyst layers sandwiched between gas diffusion media. The intimate bonding of the various layers is critical, as are catalyst functionality and membrane conductivity. If any element of the five layers is jeopardized or incorrectly assembled and then incorporated into stacks, the problem is not likely to surface until preliminary stack qualification testing. At that point the entire stack would have to be rebuilt and the suspect cells removed. This is a costly and time-consuming process. Sophisticated electroanalytical methods are now currently used to assess small, laboratory single cells, especially alternating current (ac) impedance spectroscopy from which membrane and electrode viability can be assessed. These methods have not been fully developed for online, continuous, web-based, stand-alone membrane electrode assemblies.

Program Funding

The annual funding for hydrogen and fuel cell R&D since 2003 is presented in Figure 3-5(a). The breakdown of how the funds have been appropriated with respect to fuel cell R&D since the Phase 3 review is shown in Figure 3-5(b). In the latter years it is evident that fuel cell R&D has seen a significant reduction in funding. It is also evident from Figure 3-5(b) that the bulk of the funding has focused on the most critical technical issues, namely, catalysts and membranes. This trend continues as the proposed FY 2013 budget (DOE, 2012a) for the DOE hydrogen and fuel cell R&D has been further reduced by greater than 20 percent, to about $80 million, down from $104 million in FY 2011 and $170 million in FY 2010. The fuel cell systems R&D budget, relevant to this review, has seen a decrease in funding from $75 million in FY 2010 to $43 million in FY 2012.

The budget reductions have resulted in a limited but more focused and coordinated set of initiatives (Figure 3-5[b]). Although fuel cell technology has progressed, the current status is that further advancements are still needed. The funding reductions have impacted to varying degrees the approximately 300 hydrogen and fuel cell projects currently under contract with DOE, as well as the number of new awards made under recent solicitations. Offsetting this to some



(a)

(b)

FIGURE 3-5 Historical and current Department of Energy (DOE) budgets for hydrogen and fuel cell research and development (R&D), FY 2003 through FY 2012. (a) Annual DOE funding for hydrogen and fuel cell R&D, FY 2003 through FY 2012. (b) DOE funding for various fuel cell R&D areas, FY 2010 through FY 2012. SOURCE: C. Gittleman, General Motors, and K. Epping Martin, Department of Energy, "Fuel Cell Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.; and S. Satyapal, Department of Energy, "Fuel Cell Technologies Overview," presentation to the committee, December 5, 2011, Washington, D.C.; Sunita (2011).

extent is the coordination of activities with other organizations—for example, with the Office of Basic Energy Sciences, which has contributed to key fundamental learning and advancements. It is important that conclusions regarding the status and needs of the program not be improperly derived. The benefits of prior DOE funding are just now becoming apparent and quantifiable. Over the past decade, 183 prototype vehicles have been involved in actual on-road tests, more than 500,000 vehicle trips have been documented, and 3.5 million miles have been driven—all of which have contributed to the assessment and validation of the technology *and the identification of areas requiring further technical enhancement*. This learning impacts the supply chain as well because component suppliers are responsible for developing and ultimately manufacturing what goes into a vehicle. Given that suppliers are the predominant recipient of DOE funding, budget reductions may impact them as well.

Significant Barriers and Issues

As highlighted throughout this review, cost and durability issues remain significant impediments to meeting the fuel cell program targets. Both are technical issues and must ultimately be addressed through continued activities in fundamental and applied R&D efforts.

If progress toward meeting the targets is to continue in the aforementioned topic areas, the activities addressing them must remain intact, in some cases for extensive periods of time. Although the OEMs are making progress, what is reported to the committee is not necessarily derived from the most recent technical advancements, but rather from older vehicle performance test programs that take time to develop statistically significant and meaningful results. These results then provide direction to the fuel cell technical team, followed by DOE solicitations. It is important but difficult to maintain a coordinated, longer-term, proactive effort among the various stakeholders, including the OEMs, the national laboratories, private industry, and academia, especially in the face of uncertain funding. The majority of the Fuel Cell Technologies Program funding should be directed toward next-generation technical solutions that will be important in meeting the goals of the entire program. The lack of continuity of funding as a result of budget limitations is a serious issue.

Response to Phase 3 Recommendations

The Phase 3 review presented four recommendations regarding fuel cell activities (NRC, 2010). The recommendations addressed (1) increased funding levels and support for the enhancement of key system components, including stack technology; (2) ensuring that non-OEM cost and systems modeling activities utilize the most recent, up-to-date, vehicle technical know-how, design, and componentry; (3) the development of alternative pathways in the event that the primary paths fail to yield desired results; and (4) the subjecting of currently funded nonperforming programs or efforts to an accelerated go/no-go assessment if they are deemed not to be of value to the vehicle program. It is noted by the committee that the majority of the recommendations were adequately addressed by DOE, some more so than others. Although not called out specifically in a formal response, in many cases elements of some of the recommendations can be found in existing funded programs. With that said, the recommendation to increase funding in the most critical area, specifically, stacks—that is, durability, catalyst, and membrane development—is not apparent from the FY 2010-2012 budget allocations.

Appropriateness of Federal Funding

The committee believes that R&D that has been supported by DOE related to fuel cells is appropriate for federal funding. R&D in this area is important for giving the nation a range of options for energy conversion across several applications and for providing needed energy savings and emissions reductions. Significant progress has been made to date; nonetheless, barriers that need to be addressed by research remain. Continued R&D support for fuel cells is necessary to make the progress needed to meet the ultimate goals set by DOE.

Observations and Conclusions

Based on the advancements that the automotive companies have made on their HFCVs and assuming that part of these advancements have been due to Partnership efforts, it can be concluded that significant progress has been made since the Phase 3 NRC (2010) report. It should be noted that such technologies were in part derived from DOE funding and coordinated efforts with the prior FreedomCAR and Fuel Partnership and current U.S. DRIVE Partnership programs. Furthermore, investigations on fundamental issues related to durability and performance have been expanded in scope and have begun to yield insight not only into degradation mechanisms but also in terms of providing guidance for developing next-generation catalysts and electrodes. Both are necessary if the performance targets are to be met. Progress has been made in other areas as well and should not be dismissed. It is important to provide continuous support for R&D in these areas if targets are to have any likelihood of being met.

Fuel cell stack cost and durability are still the two major areas that have not simultaneously met targeted levels. Stack lifetimes have exceeded 50 percent of the targeted 5,000 hours in real-world on-road vehicles. Fuel cell costs for a 500,000 per year production level have been projected to have dropped since the last report, from \$60-\$70/kW in 2009 to \$49/kW in 2011.[9] Further reductions

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[9] C. Gittleman, General Motors, and K. Epping Martin, Department of Energy, "Fuel Cell Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

will potentially come over time, as learning from on-road vehicle performance and technologies with reduced platinum loadings are adopted. Advanced catalysts have been and continue to be developed, including platinum-free systems. Such programs have emanated from academia, industry, and, most important, from the national laboratories. New developments take significant time and testing resources by the fuel cell OEMs before they can be fully adopted. This activity represents significant financial resources.

Statements by OEMs in this country and by other global automotive companies have indicated that vehicles in limited quantities will be placed in predetermined locations worldwide, partly gated by the availability of hydrogen refueling facilities, in the 2014-2016 time frame. This activity coincides with the timing of the original technology roadmap milestone of the FreedomCAR and Fuel Partnership whereby in 2015 there would be a commercialization readiness decision. Considering the global economic downturn and the budget constraints of late, the vehicle engineering accomplishments attest to the commitment of automotive manufacturers to fuel cell vehicles and thus to the importance of the Partnership's enabling R&D. The expected onset of fuel cell vehicle deployment is impressive.

Activities within the program encompass not only the technical elements of the stack but also a number of focus areas that address market adoption and analyses, as well as a host of technical and nontechnical topics. In light of the budget data presented in Figure 3-5 and the criticality of the technical issues (durability and cost), the "balance" of the entire program as assessed by the percentage of funding in less critical areas over others of greater importance can be called into question.

Recommendations

The adoption of fuel cell vehicles is partly dependent on the durability and the cost of the technology. Fuel cell development is an important element of the U.S. DRIVE Partnership and, if successful, the chances of meeting the long-term goal of reducing greenhouse gas emissions and U.S. dependence on foreign oil are increased. Fuel cell R&D activities that address the remaining technical challenges and costs have decreased annually since the NRC's Phase 3 review. This decline negatively impacts the development of future solutions that the developers will have available to meet the near- and long-term targets.

Enhanced catalyst, electrode, and membrane robustness would improve the likelihood that fuel cell stacks achieve the 5,000-hour life target. Such research efforts are generally long-term programs, as new catalysts, membranes, and related stack initiatives must progress from fundamental research activities all the way through lifetime and performance testing, and then vehicle qualification. These types of R&D activities must remain a high priority in order to ensure that next-generation robust stack component solutions become available.

Recommendation 3-3. The DOE should increase the efforts related to the development of new catalysts, membranes, and related membrane electrode assembly components for proton exchange membrane (PEM)-based fuel cells. The focus should be on materials, performance, durability, and, ultimately, on manufacturability.

As noted throughout this major section on fuel cells, cost is the other major challenge besides durability. There are two primary cost-reduction pathways: subsystem process optimization and specific component cost-reduction initiatives. For example, technical innovations might result in the simplification or elimination of subsystems or, when it comes to stack components, lower platinum loadings as well as lower-cost membranes and plate hardware. Emerging modeling capabilities can be used for sensitivity analysis and can guide resource allocation to the areas that will have the greatest impact on performance, endurance, and cost at the system level.

Recommendation 3-4. The DOE should increase efforts for the cost reduction initiatives for fuel cells taking into account the entire system, including balance of plant. Emerging modeling capabilities should be used for sensitivity analysis and for guiding resource allocation to the areas that will have the greatest impact on performance, endurance, and cost at the system level.

A number of emerging alternative fuel cell concepts, if successfully developed, may provide options for the OEMs in future generations of fuel cell vehicles. An alkaline fuel cell that uses membrane technology is one such example; a fuel cell concept that employs a flowing catholyte concept is another. Although PEM technology is well embraced by the automotive OEMs, it is imperative that novel fuel cell concepts be assessed critically and, if considered potentially attractive, also be explored and, as appropriate, directly or indirectly supported by DOE in its long-term, high-risk portfolio of projects.

Recommendation 3-5. Either in coordination with other organizations, such as the Office of Basic Energy Sciences or DOE's Advanced Research Projects Agency-Energy (ARPA-E), or directly, DOE should consider supporting new and innovative alternative fuel cell concepts.

High-volume manufacturing methods for fuel cell stack components, in particular for the membrane and electrode assemblies, will need to incorporate (electro-) analytical quality-control methods to assess membrane and electrode viability prior to assembly into stacks. Such methods are utilized in laboratory fuel cells, but they are not currently developed for high-speed web-based manufacturing processes. If successfully developed, the information will be able to identify stacks that have inherent flaws within the membrane, interfacial region, and electrode layers.

Recommendation 3-6. U.S. DRIVE should encourage projects that address the use of real-time, in situ electroanalytical quality-control methods to assess membrane and electrode performance characteristics during the continuous manufacturing web-based process.

ONBOARD HYDROGEN STORAGE

Background

The mission of the hydrogen storage technical team is to "accelerate research and innovation to achieve commercially viable hydrogen storage technologies that meet U.S. Drive goals."[10] The onboard hydrogen storage goal is for "a >300 mile driving range across different vehicle platforms without compromising passenger/cargo space or performance." The program scope is to "review and evaluate materials and systems research regarding hydrogen storage onboard light-duty vehicles and provide feedback to DOE and partnership stakeholders . . . generate goals and performance targets for hydrogen storage onboard vehicles . . . collaborate with other technical teams and assist the partnership in regards to hydrogen storage." The work of the hydrogen storage technical team on onboard storage is most important to the U.S. DRIVE Partnership as a whole given the criticality of hydrogen storage to the performance of PEM fuel-cell-powered vehicles. The hydrogen storage system characteristics determine the amount of hydrogen that can be stored on the vehicle and the corresponding miles traveled between refueling as well as fuel storage costs.[11]

Materials-based solutions are the long-term option for onboard hydrogen storage. In the past decade, DOE established four hydrogen storage centers of excellence (COEs). Three materials centers of excellence (Chemical Hydrogen Storage COE, Metal Hydrides COE, and Hydrogen Sorption COE) operated from 2005 through 2010 and are now closed; final reports were issued April 2012.[12] The fourth is the Hydrogen Storage Engineering COE. The COE proved to be an outstanding management concept that enabled the assembly of the right skills and resources for good collaboration to be brought to the work, a systematic down-select decision process, high-quality and consistent communication among the partners, and the development of intellectual property. Through these centers of excellence more than 400 compounds were investigated for their hydrogen sorption and release characteristics, and computationally millions of materials were studied. The work of these centers and related independent projects was a

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[10] N. Stetson, Department of Energy, and S. Jorgensen, General Motors R&D, "Hydrogen Storage Tech Team," presentation to the committee, January 26, 2012, Washington, D.C. Also see http://www.hydrogen.energy.gov/storage.html.

[11] See http:/www.hydrogen.energy.gov/annual_review10_proceedings.html and http://www.hydrogen.energy.gov/annual_progress11.html.

[12] See http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage.

well-organized systematic effort. This work involved extensive collaborations. In total, 45 universities, 15 companies, and 15 federal laboratories participated. A number of materials identified in this work are still considered to have potential, but storage weight, volume, performance, and cost are still a challenge. A brief description of the center accomplishments follows.

- *Chemical Hydrogen Storage COE.* Los Alamos National Laboratory, the lead laboratory for the Chemical Hydrogen Storage COE, worked closely with PNNL and other partners. A major accomplishment of the center was to demonstrate that chemical reprocessing of spent fuel is feasible. The highest-capacity material identified was based on ammonia borane, which was shown to release 2 to 2.5 moles of hydrogen (13-16 weight percent [wt%]) below 200°C with good stability. Research studies led to new understanding of the kinetics and nucleation of dehydrogenation. Additional findings related to materials processing and materials modification for improved performance and for ease of regeneration at a favorable cost. The COE received 16 patents.
- *Hydrogen Sorption COE.* The Hydrogen Sorption COE, led by NREL, was challenged to obtain high gravimetric and volumetric storage of hydrogen compared with compressed storage and at ambient temperatures. Work was focused on materials that gave excess storage capacities greater than 6 wt% and 40 g/L at pressures less than 200 bar (ca. 20 MPa) and storage temperatures above 77 K. Major findings overall include new materials for cryogenic storage on high specific surface area sorbents by optimizing pore size distributions, metal organic frameworks that exhibit enhanced di-hydrogen binding, and ambient-temperature storage by means of spillover and coordinatively unsaturated metal clusters. Also, measurement capabilities were improved and materials design was accelerated with coupled theory and experimental efforts. The COE produced more than 200 peer-reviewed publications, stimulated progress worldwide, and fostered spin-off for other sorption applications.
- *Metal Hydride COE.* The Metal Hydride COE, which was led by SNL, had five projects: (1) destabilized hydrides with enhanced kinetics ($LiBH_4/Mg_2NiH_4$); (2) complex anionic hydride materials (e.g., boron hydride); (3) amide/imide storage materials (e.g., LiMgN); (4) alane; and (5) engineering analysis and design. The COE expanded the knowledge of metal hydrides hydrogen storage material and issued 279 publications. The boron hydride system showed remarkable properties reversibly, storing 12 wt% hydrogen. In spite of these favorable properties, no single material was identified that meets all criteria. A breakthrough theoretical method was developed for the rapid screening of materials, and a new theoretical method, prototype electrostatic ground state, from the theory group enables the prediction of crystal structures of unknown compounds.

TABLE 3-3 FY 2010-FY 2012 Hydrogen Storage Research and Development Budget and FY 2013 Budget Request

Year	Budget ($ millions)
FY 2009 appropriated	59.20
FY 2010 appropriated	32.00
FY 2011 appropriated	15.00
FY 2012 appropriated	17.50
FY 2013 requested	13.00[a]

[a] Hydrogen Storage is included within the Hydrogen Fuel R&D request ($27 million).

SOURCES: DOE (2010a, 2011); Stetson (2010, 2011, 2012); S. Satyapal, Department of Energy, "Fuel Cell Technologies Overview," presentation to the committee, December 5, 2011, Washington, D.C.

- *Hydrogen Storage Engineering COE.* The more recently established Hydrogen Storage Engineering COE at Savannah River National Laboratory (SRNL) has as its mission to "address significant engineering challenges associated with the development of lower pressure materials based hydrogen storage systems for hydrogen fuel cell and internal combustion engines for light duty vehicles."[13] Reported accomplishments to date include the development of hydrogen storage system models, the establishment of a baseline for materials properties that is used to guide the development of storage systems, assessment of the current status of all storage system approaches versus targets, and the identification of technology gaps that help to focus R&D. Modeling work on metal hydride hydrogen storage systems was completed.

The coordination with the DOE Office of Basic Energy Sciences is continuing. Twenty BES-funded projects were included in the Annual Merit Review held in May 2012. Work is underway to strengthen all national collaborations (within the DOE and across agencies including the U.S. Department of Transportation [DOT], the U.S. Department of Defense [DOD-Defense Logistics Agency], the National Institute of Standards and Technology [NIST], and the National Science Foundation [NSF]).

The FY 2011 budget for the onboard hydrogen storage activities has seen a decrease of 75 percent from FY 2009 and a 60 percent decrease in the number of projects for the same time period. The materials development work has experienced the largest decrease, with the closing of three materials centers of excellence. New work on advanced compressed gas tanks is anticipated in the FY 2012 budget plan. See Table 3-3 for recent appropriations and the FY 2013 budget request for hydrogen storage R&D.

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[13] See http://hsecoe.srs.gov/mission.html.

Current Status Versus Targets

A new roadmap that will guide the research is in final development, having been last updated in 2007. The target levels for onboard hydrogen storage first established in 2003 are in review. The DOE is reevaluating the performance metrics in comparison to available fuel cell, hybrid, and electric vehicle performance data. The current and projected target levels are shown in Tables 3-4 and 3-5.

The capabilities of various storage systems have been determined from engineering models of the various technologies. Progress is being made, and several targets have been met for some technologies, but no technology meets all targets simultaneously. Cost is an issue for all technologies.

The key system issues and challenges have been identified in terms of the following criteria:

- Sufficient storage for driving range without impacting vehicle performance,
- Kinetics,
- Safety,
- Capacities,

TABLE 3-4 Onboard Hydrogen Storage Technical Targets, 2010, 2017, and Ultimately

Target	Units	2010	2017	Ultimate
System gravimetric density	wt%	4.5	5.5	7.5
	kWh/kg	1.5	1.8	2.5
System volumetric density	g/L	28	40	70
	kWh/L	0.9	1.3	2.3
System fill time for 5-kg fill	min	4.2	3.3	2.5
	kg H_2/min	1.2	1.5	2
System cost	\$/kg H_2 \$/kWh_{net}	TBD	TBD	TBD
Minimum delivery temperature	°C	–40	–40	–40
Maximum delivery temperature	°C	85	85	85
Minimum full flow rate	(g H_2/s)/kW	0.02	0.02	0.02
Onboard efficiency	%	90	90	90
Cycle life (1/4 tank to full)	Cycles	1,000	1,500	1,500
Fuel cost	\$/gge at pump	3-7	2-4	2-4
Loss of usable H_2	(g H_2/hr)/kg H_2	0.1	0.05	0.05
"Well" to power plant efficiency	%	60	60	60
Fuel purity	% dry basis	99.97	99.97	99.97
Transient response	s	0.75	0.75	0.75
Start time to full flow (–20°C)	s	15	15	15
Start time to full flow (20°C)	s	5	5	5

NOTE: TBD, to be determined.

SOURCE: See http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf; N. Stetson, Department of Energy, and S. Jorgensen, General Motors R&D, "Hydrogen Storage Tech Team (HSTT)," presentation to the committee, January 26, 2012, Washington, D.C.

TABLE 3-5 Current Status of Various Onboard Hydrogen Storage Technologies

Current Status	Gravimetric (kWh/kg-system)	Volumetric (kWh/L-ystem)	Cost ($/kWh)
700 bar (ca. 70 MPa) compressed (Type IV)[a]	1.7	0.9	18.9
350 bar (ca. 35 MPa) compressed (Type IV)[a]	1.8	0.6	15.5
Cryo-compressed (276 bar)[a]	1.9	1.4	12
Metal hydride (NaAlH4)[b]	0.4	0.4	11.3
Sorbent (MOF-5; 200 bar)[b]	1.7	0.9	18
Off-board regenerable (AB)[b]	1.4	1.3	N/A

NOTE: Cost targets are being finalized and are expected to be released soon. Also, the Environmental Protection Agency (EPA) defines 33.7 kWh of electricity as equivalent to 1 gallon of gasoline. AB, ammonia borane; N/A, not available.

[a] Based on TIAX/ANL projections.

[b] Based on Hydrogen Storage Engineering Center of Excellence projections.

SOURCE: Stetson (2012).

- Impurities,
- Heat management,
- Efficiency,
- Cost,
- Durability, and
- Engineering and manufacturing.

In spite of rather rapid and impressive advances in hydrogen storage capacity by metal organic frameworks (MOFs) and covalent organic frameworks (COFs), the temperature and pressure required to achieve high capacities are far from DOE's targets, and there are no systems identified yet that can do so.

System cost has proven to be a challenge for all promising materials and systems. Currently 80 percent of the hydrogen sorption projects have been discontinued on the basis of budgets or project results. Down-selects (go/no-go points) led to a decision to stop hydrolysis program work. Project down-selects by the Hydrogen Storage Engineering COE have resulted in phasing out work on metal hydrides (75 percent discontinued) and solid-phase chemical hydrogen (95 percent discontinued) materials engineering. Clearly, creative ideas need to be developed, and a plan is needed that will lead to fundamentally new ideas.

Compressed gas storage is the near-term path to commercialization. Compressed gas storage levels at 35 MPa and 70 MPa are near to the 2015 target for gravimetric storage but are only about 45 percent and 66 percent, respectively, of the volumetric target. The 70 MPa is preferred by the automotive OEMs because it offers greater vehicle range and is becoming the de facto standard storage pressure, but it can lead to additional refueling costs for pre-cooling and higher compression energy. The National Aeronautics and Space Administration (NASA) White Sands Facility offers expertise in composite pressure vessel testing, including pressure failure analysis, nondestructive evaluation, structural analysis, burst tests, and fire safety.[14]

Assessment of Progress and Key Achievements

Key achievements since the NRC (2010) Phase 3 review are in the area of cryo-compressed hydrogen, hydrogen sorbents, chemical hydrogen storage, and metal hydrides. The cryo-compressed system has demonstrated 10.4 kg of usable capacity that is greater than the 2017 target, but the cost is estimated to be $12/kWh. A smaller tank has been designed that delivers 5.6 kg of H_2 (LLNL). The tank must be filled with liquid hydrogen to achieve maximum capacity, and the length of time that the tank is idle before venting hydrogen (dormancy) is an issue.

Two hydrogen sorbents have exhibited materials capacities greater than 8 wt% and 28 g/L at 77 K and 7 MPa. This work was done at Northwestern University (Cu-MOF, a copper-containing metal organic framework) and at Texas A&M University (PPN[porous polymer network]-4(Si)). PPN-4(Si) is a highly stable porous polymer network with ultrahigh gas uptake capacity. Chemical hydrogen storage systems are on a path to exceed the 2017 system targets, but off-board regeneration efficiency is still an issue. Ammonia borane and alane, chemical hydrogen storage materials, have demonstrated release kinetics and spent fuel regeneration. Both materials have greater than 10 wt% hydrogen (LANL/PNNL and Brookhaven National Laboratory [BNL]/SRNL). One metal hydride, $Mg(BH_4)_2$, has demonstrated a reversible material capacity of greater than 12 wt%, but the temperature and pressure are too extreme for onboard use (University of Hawaii and SNL).

The Hydrogen Storage Engineering COE provides a coordinated approach to the engineering R&D of materials-based hydrogen storage. This COE has completed an integrated system model for hydrogen storage and established a state-of-the-art baseline against the 2010 targets for all three materials classes. This modular approach allows each system to be run through simulated drive cycles to predict performance. This work has enabled the COE to down-select systems for further development.

Compressed hydrogen is the near-term option for onboard hydrogen storage. A major barrier, however, is the cost of the storage system, cited to be $2,800 for a 5-kg H_2 system.[15] The U.S. DRIVE Partnership defines 1 kg of hydrogen to be equivalent to 1 gallon of gasoline. A 300-mile driving range will thus require 5 to 10 kg of hydrogen depending on vehicle characteristics such as size and weight. Approximately 75 percent of the cost is the carbon-fiber composite and 50 percent of that cost is the precursor fiber. The DOE, in concert with the U.S.

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[14] See http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080029396_ 2008026596.pdf.

[15] N. Stetson, Department of Energy, and S. Jorgensen, General Motors R&D, "Hydrogen Storage Tech Team (HSTT)," presentation to the committee, January 26, 2012, Washington, D.C.

DRIVE hydrogen storage technical team, has recently initiated several projects that address cost:

- Development of textile-grade polyacrylnitrile, PAN (ORNL),
- Development of melt spinable PAN (ORNL-Virginia Polytechnic Institute and State University),
- Development of nano-reinforced CFCs (Applied Nanotech, Inc.; SBIR), and
- Investigation of basalt glass fibers (Quantum Technologies; SBIR).

The first project aims to produce high-strength carbon fibers from commodity textile-grade PAN fibers.

A workshop with various stakeholders was held in February 2011 to address opportunities for cost reduction of composite storage tanks.[16]

In December 2011, DOE announced four projects totaling more than $7 million to advance hydrogen storage technologies for fuel cell electric vehicles. These 3-year projects are listed in Table 3-6.

Committee members conducted site visits with two DOE contractors for hydrogen storage tank development related to the U.S. DRIVE objectives: Lincoln Composites and Quantum Technologies. (See Appendix D, "Committee Meetings and Presentations.") These visits provided an understanding both of the challenges and the costs of high-pressure storage and of the manufacturing processes. Lincoln Composites is working with the Engineering Center of Excellence on material filled tanks. Committee members also visited Structural Composites, Inc., a manufacturer of Type 3 tanks.[17] Following these visits, the committee members are optimistic that the cost of hydrogen storage tanks (Type 4 tanks) can be reduced in the future through reduced materials and manufacturing costs. Cost reduction is not likely in the near term. These companies also manufacture tanks for natural gas storage, which is a rapidly growing business area.

International Activities

Hydrogen storage is an area of keen interest within the various international fuel cell programs. These programs, which have representation from many countries, include the International Energy Agency, the International Partnership for a Hydrogen Economy, and the International Institute for Carbon-Neutral Energy Research (Japan). The DOE is an active participant in these programs and has a significant number of its projects "endorsed" by these groups. For example, an international task force was established to confirm whether excess

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[16] See http://www2.eere.energy.gov/hydrogenandfuelcells/wkshp_compressedcryo.html.

[17] The Type 3 tank is composed of a metal liner reinforced by fiberglass or carbon fiber applied in a full wrapped pattern around the entire liner. The Type 4 tank is composed of a plastic gas-tight liner reinforced by carbon fiber or fiberglass around the entire liner.

TABLE 3-6 Recent Hydrogen Storage Technology Projects Awarded by the Department of Energy

Institutions	Amount ($ millions)	Activity
PNNL with Lincoln Composites, Ford, Toray Carbon Fibers America, Inc., AOC, Inc.	2.10	Lower the cost of manufacturing of hydrogen storage tanks by more than 30 percent relative to current projections
HRL Laboratories, LLC	1.20	Innovative approach to hydrogen storage using engineered liquids that absorb and release hydrogen gas
LBNL with NIST, GM	2.10	Theory-guided synthesis of novel hydrogen storage materials
University of Oregon with University of Alabama, PNNL, Protonex Technology	2.00	Develop and test promising new chemical storage materials

NOTE: PNNL, Pacific Northwest National Laboratory; LBNL, Lawrence Berkeley National Laboratory; NIST, National Institute of Standards and Technology.
SOURCE: See www.EERE.energy.gov/hydrogen&fuelcell/news.

adsorption at room temperature can be increased by hydrogen spillover from a catalyst site on a high-surface-area catalyst support material. Further progress on hydrogen storage in other countries supports the goals of the U.S. DRIVE program (Stetson, 2012).

Significant Barriers and Issues That Need to Be Addressed

Although progress continues to be made in solid-state storage, key characteristics have not all been met with any single material. Cost is a significant barrier for all systems. Given the cuts in the hydrogen storage budget, the Partnership is not on a path to overcome these barriers. Basic research and generation of new ideas are needed. One example is the need for R&D on liner materials for cryo-compressed hydrogen storage.

The development of a hydrogen fueling infrastructure that anticipates and leads vehicle introduction is in need of support to ensure that the fueling infrastructure is in place in advance of vehicle introduction. The timely build-out of the hydrogen refueling infrastructure is a potential significant barrier.

Responses to Recommendations from Phase 3 Review

The recommendations and responses to recommendations from the NRC (2010) Phase 3 review are listed below. These responses were written prior to the latest round of budget cuts, and DOE may no longer be in a position to follow through on the cited plans. The full text of the responses to the recommendations is available in the file entitled "Actions, Evidence, and Responses to the Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report, December 2012," which is available in the National Academies Public Access File for this Phase 4 review.

- *NRC Phase 3 Recommendation 3-9.* The NRC (2010) Phase 3 report recommended that the most promising approaches for hydrogen storage be continued, that the centers of excellence that were being closed document their findings for the completed R&D, that contractor reports be available through EERE, and that basic research activities on hydrogen storage continue. The DOE responded that it agrees with this committee recommendation. It will continue to fund independent projects that address applied materials work on H_2 storage. The centers of excellence will complete summary reports, a database for materials performance data from the materials centers will be established, and the partner final reports will be public documents. The BES will continue to fund basic research in H_2 storage materials and crosscutting research through its Hydrogen Fuel Initiative Projects and Core Research Programs.
- *NRC Phase 3 Recommendation 3-10.* The NRC (2010) Phase 3 report recommended that research on compressed gas storage be expanded to safety-related activities that determine cost and weight. The DOE agrees that safety is paramount and critical during the development of all hydrogen storage technologies. Safety is included in all development projects. One significant accomplishment involves the development of SAE J2579, "Recommended Practices for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles." The DOE has participated in and hosted international workshops on hydrogen safety-related technologies including codes and standards.
- *NRC Phase 3 Recommendation 3-11.* The NRC (2010) Phase 3 report recommended that R&D continue on the reduction of the cost of aerospace-quality carbon fiber and alternative fibers for compressed hydrogen storage. The DOE agrees with this recommendation and cited several significant activities related to this effort.
- *NRC Phase 3 Recommendation 3-12.* The NRC (2010) Phase 3 report recommended that, given the critical part that hydrogen storage is to the hydrogen and fuel cell part of the FreedomCar and Fuel Partnership, it should continue to be funded, and the funding should include the work of the Hydrogen Storage Engineering COE. The Phase 3 report recommended that effort be directed to low-pressure materials storage and to compressed-gas storage to help achieve weight reductions while maintaining safety. The DOE agrees with this recommendation and cited projects and programs both underway and proposed.

- *NRC Phase 3 Recommendation 3-13.* The NRC (2010) Phase 3 report recommended that concepts beyond materials properties be explored for reducing refueling time. The DOE responded that it will continue to work on materials with favorable thermodynamic properties and improved sorption kinetics.
- *NRC Phase 3 Recommendation 3-14.* The NRC (2010) Phase 3 report recommended that effort be made to anticipate ways in which hydrogen storage material properties might impact system performance—for example, purity, lifetime, and safety. The DOE agrees with this recommendation and has programs in place that address this concern.
- *NRC Phase 3 Recommendation 3-15.* The NRC (2010) Phase 3 report recommended a balanced long-term/short-term joint portfolio for onboard hydrogen storage. The DOE agrees with the committee recommendation and states that it continues to fund both long-term and short-term projects and will give careful consideration to achieving a balanced portfolio.

Appropriate Federal Role

The work on onboard hydrogen storage is appropriate for federal support, given the critical importance of fuel cell vehicles to the goals for fuel savings and reduction in both criteria and greenhouse gas emissions. Advanced hydrogen storage technologies need to be developed in order to meet all of the performance metrics. Ongoing high-risk basic research is needed, given the complexity and scope of this challenge. The capabilities of the national laboratories, as well as of university laboratories given the necessary government support, are well equipped to contribute to addressing this challenge.

Recommendations

The U.S. DRIVE automotive OEMs have adopted 70 MPa compressed-gas storage for near-term onboard vehicle hydrogen storage.

Recommendation 3-7. The U.S. DRIVE Partnership should re-examine high-pressure compressed-gas storage and reach a consensus as to whether this is a long-term solution or just a transition technology. Short-term and medium-term performance targets should be developed specifically for compressed tanks because such tanks are expected to be used at least on the first generation of hydrogen fuel cell vehicles. Then there should be long-term general materials targets that basic research can use for benchmarking.

Recommendation 3-8. The U.S. DRIVE Partnership should investigate the relationship between the onboard hydrogen storage tank pressure and the hydrogen infrastructure so that trade-offs can be worked out.

Cost is an issue for the compressed-gas storage tanks.

Recommendation 3-9. The U.S. DRIVE Partnership should consider joint programs with the U.S. Department of Defense and the National Aeronautics and Space Administration, which undoubtedly have similar goals for lower-cost aerospace-quality carbon fibers. Work with the newly constructed ORNL Carbon Fiber Technology Facility should also be explored.

There is a potential relationship between tank cost and safety criteria.

Recommendation 3-10. The U.S. DRIVE Partnership should demonstrate the safety of lower-cost, lighter-weight compressed-hydrogen tanks with a rigorous testing program, for example, by statistically demonstrating stress rupture toughness, fatigue life, and fire safety. In implementing such an activity, it should consider cofunding the related tests proposed by the NASA White Sands facility.

Fundamental R&D directed to onboard hydrogen storage has contributed to progress and understanding that has aided decision making.

Recommendation 3-11. The DOE (e.g., the Office of Basic Energy Sciences, the Office of Energy Efficiency and Renewable Energy, the Advanced Research Projects Agency-Energy) should initiate a new program that builds on the excellent progress made to date and expands into fundamentally new hydrogen storage research areas. A critical assessment of prospects for, and barriers to, advanced storage techniques and concepts should form *the first part* of this initiative.

ELECTROCHEMICAL ENERGY STORAGE

Background

Electric drive vehicles have great promise of dramatically reducing or even eliminating U.S. dependence on imported petroleum and the harmful greenhouse gas emissions currently associated with light-duty vehicles (provided that GHG emissions in the production of electricity are controlled). Electrochemical energy storage technology (including batteries and supercapacitors) is a key enabler for all electric drive vehicles, including hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and hydrogen fuel cell vehicles (HFCVs). (Fuel cell electric vehicles have evolved into fuel cell hybrid electric vehicles that utilize electrochemical energy storage systems to capture regenerative braking energy and to provide for a smaller fuel cell system with optimized efficiency operation.)

In the near term, HEVs utilizing high-power batteries have the best opportunity for substantial impact due to their lower cost and higher commercial viability. An improved intermediate solution could be provided by plug-in hybrid electric vehicles (PHEVs) using high-energy batteries. In the long term, the full advantage of electric drive vehicles could be realized with BEVs and/or fuel cell hybrid electric vehicles (Wagner et al., 2010). Both would use batteries or similar devices, but fuel cell hybrid electric vehicles will require high-power batteries or supercapacitors, and BEVs will require high-energy batteries. Thus, both high-power and high-energy batteries are of interest for the short and long term.

The U.S. DRIVE Partnership has provided for an intensification of R&D efforts in a portfolio of high-energy and high-power battery and supercapacitor technologies. This effort has included a wide range of activities, from basic research at the materials level, to new device development, all the way to systems-level prototype development aimed at meeting performance and cost objectives. The status of manufacturing development and cost reduction of these technologies has also been advanced through large capital contracts issued through American Recovery and Reinvestment Act of 2009 (ARRA) funding for the building of battery plants for electric drive vehicle applications.

The past decade has seen the commercial development of HEVs, based in part on the previous successful development of high-power batteries supported by the U.S. DRIVE Partnership through the United States Advanced Battery Consortium (USABC). However, the HEV market share remains somewhat flat, at around 3 percent of U.S. new-car sales. Innovations are still needed, particularly to overcome battery cost impediments.

Due in part to more than a decade of extensive DOE-funded lithium-ion (Li-ion) battery R&D, this technology is now starting to show tangible commercial progress in automotive applications. High-energy Li-ion batteries are enabling several high-profile BEV and PHEV production programs, including the Tesla Model S, GM Volt, and Nissan Leaf. About 20,000 of these vehicles were sold in the United States in 2011. Additionally, Li-ion batteries are now being commercialized in hybrid vehicles, recently showcased in numerous automotive OEM models displayed at the 2012 North American International Auto Show. Most notably, Ford, the largest U.S. manufacturer of HEVs, is planning to discontinue nickel metal hydride batteries in its vehicles in favor of higher-power Li-ion batteries, starting in 2013. With GM also introducing Li-ion batteries in new HEV models, the U.S. automotive companies are at the forefront of advanced battery technology for electric drive vehicles.

The DOE Vehicle Technologies Program, in collaboration with the USABC, manages the electrochemical energy storage technology activities with a goal of the advancement of electrochemical energy storage technologies, to enable the U.S. DRIVE partners to introduce electric drive vehicles with the potential to reduce U.S. dependence on petroleum and harmful vehicle emissions (DOE, 2010b, 2012a,b). Technology development is undertaken by battery manufacturers, DOE national laboratories, and universities. As in recent years, the main effort is now composed of four main subactivities: (1) Battery Development, (2) Applied

Battery Research, (3) Exploratory Materials Research, and (4) Testing, Analysis, and Design (Howell, 2012).[18]

The Battery Development subactivity encompassing battery module and system hardware development and related activities was largely directed by USABC, funding more than a dozen major programs, with a variety of companies developing batteries, supercapacitors, components, and materials aimed at BEV, PHEV, and HEV applications. Applied Battery Research activities were directed and carried out by the national laboratories, with ANL in the lead role; these activities focused on the next-generation, high-energy Li-ion battery couples with a potential to meet challenging requirements for the 40-mile all-electric-range PHEV. Exploratory Battery Research (previously known as the Batteries for Advanced Transportation Technologies Program) addressed the fundamental understanding of specific electrochemical systems for lithium batteries and the development of newer couples with a potential for higher power and higher energy density. This exploratory work, directed by the Lawrence Berkeley National Laboratory, was carried through many top academic groups with the participation of national laboratories and industrial research groups as well. The newest program, Testing, Analysis, and Design, was initiated in 2011 to address testing, modeling, and computer design tool development.

In addition to the battery R&D activities of the DOE VTP and USABC, which U.S. DRIVE is most directly involved with, U.S. DRIVE longer-term objectives are being pursued by DOE-funded R&D in the new ARPA-E organization. These efforts are aimed at high-risk transformational (game-changing) technologies beyond the projected capabilities of Li-ion batteries that have been the central R&D focus for a decade. More broad fundamental R&D activities are also pursued by the DOE Basic Energy Sciences program. Finally, an Energy Innovation Hub on batteries is being formed in 2012 by DOE because of the perceived need for a multidisciplinary, multi-institutional integrated research organization to address this strategically important field.

In a related activity, funding from the ARRA enabled DOE to provide $1.5 billion in grants for producing batteries and their components. Since the Phase 3 NRC (2010) review, several of these plants are now in production. Very useful information related to manufacturing process technology and production costs is being provided to the program (DOE, 2012b).

Current Status Versus Goals and Targets

Overall the goal is to develop electrochemical energy storage systems that will enable electric drive vehicles that can substantially reduce both U.S. dependence on petroleum and GHG emissions without sacrificing vehicle performance.

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[18] D. Howell, Department of Energy, and R. Elder, Chrysler, "Electrochemical Energy Storage Technical Team (EEST)," presentation to the committee, January 26, 2012, Washington, D.C.

These vehicles include a progression of technology from HEVs to PHEVs to BEVs and HFCVs. DOE energy storage targets adapted from the USABC technical targets are provided in Table 3-7 (DOE, 2010a).

HEV Batteries Meet Performance Targets But Exceed Cost Targets

Although there remains some uncertainty about calendar life, at least the initial performance targets for high-power batteries for power-assist hybrid vehicles have been generally met by both nickel-metal hydride and Li-ion high-power battery technologies, with the exception of cost. High costs, exceeding targets by about 50 percent, remain a barrier for the more widespread commercialization of hybrid vehicles.

Supercapacitors may offer a more cost-effective solution for HEVs. However, they do not currently meet the available energy target of 0.3-0.5 kWh within the weight and volume restraints above. Recently, modeling and experimental R&D at NREL have scrutinized this target, providing strong evidence that only a fraction of this targeted available energy is needed for the HEV application. Consequently, USABC has added a new set of performance targets, called High Power Low Energy—Energy Storage System targets, and funded Maxwell Technologies to develop supercapacitors for HEV applications (U.S. DRIVE, 2011; Snyder, 2012).

TABLE 3-7 Department of Energy Technical Targets for Energy Storage Technologies for Hybrid Electric Vehicles (HEVs), 2010; Plug-in HEVs (PHEVs), 2015; and Electric Vehicles (EVs), 2020

Storage Technology Characteristics	HEV (2010)	PHEV (2015)	EV (2020)
Equivalent electric range, mi	N/A	10-40	200-300
Discharge pulse power, kW	25-40 for 10 sec	38-50	80
Regen pulse power (10 s), kW	20-25	25-30	40
Recharge rate, kW	N/A	1.4-2.8	5-10
Cold cranking power @ –30°C (2 s), kW	5-7	7	N/A
Available energy, kWh	0.3-0.5	3.5-11.6	30-40
Calendar life, years	15	10+	10
Cycle life, cycles	300,000, shallow	3,000-5,000, deep discharge	750, deep discharge
Maximum system weight, kg	40-60	60-120	300
Maximum system volume, liters	32-45	40-80	133
Operating temperature range, °C	–30 to 52	–30 to 52	–40 to 85
Selling price at 100,000 units per year, $	500-800	1,700-3,400	4,000

NOTE: N/A, not available.
SOURCE: DOE (2010b).

PHEV Batteries Approach Performance Targets But Exceed Cost Targets

Lithium-ion high-energy battery technology has progressed to be capable of meeting the performance goals for PHEV applications at the systems level with the exception of cost, which still exceeds the cost target by a factor of two (DOE, 2012b).

BEV Batteries Fall Short on Specific Energy and Greatly Exceed Cost Targets

Lithium-ion high-energy battery technology has substantially exceeded the capabilities of previous battery technologies aimed at BEV applications, with substantial progress in the past decade, in part due to the concentrated efforts of DOE in coordination with the U.S. DRIVE Partnership. However, current Li-ion BEV batteries are too heavy by about a factor of two on a system basis. More seriously, they currently cost too much by a factor of four or more versus USABC cost targets. Yet there have been some optimistic cost projections for the rest of the decade, some at less than $300/kWh in the 2015-2020 time frame. However, these costs are still double the official USABC cost targets (DOE, 2012b). The status of BEV battery performance versus technical targets is given in Table 3-8.

Technical Targets Need Revision

Over the years, a variety of detailed technical targets for electrochemical energy storage systems for a variety of electric drive vehicle applications have

TABLE 3-8 Status of Electric Vehicle Battery Performance, Current Status Versus Technical Targets for All-Electric Vehicles (AEVs), 2020

Energy Storage Goals	AEV (2020)	Current
Equivalent electric range, mi	200-300	√
Discharge pulse power (10 s), kW	80-120	√
Regenerative pulse power (10 s), kW	40	√
Available energy, kWh	40-60	√
Recharge rate, kW	120	50
Calendar life, years	10+	TBD
Cycle life, cycles	1,000 deep cycles	TBD
Operating temperature range, °C	+40-60	0-40
System weight, kg	160-240	500-750
System volume, liters	80-120	200-400
Production cost at 100,000 units per year, $/kWh	125	<600

NOTE: Initial electric vehicle (EV) battery development contracts were started in FY 2011. Focus on high-voltage/high-capacity cathodes and electric vehicle cell design optimization. Data based on initial work from USABC Envia Systems and Cobasys/SBLimotive contracts. TBD, to be determined.
SOURCE: D. Howell, Department of Energy, and R. Elder, Chrysler, "Electrochemical Energy Storage Technical Team (EEST)," presentation to the committee, January 26, 2012, Washington, D.C.

been developed by various organizations, including USABC, the Partnership for a New Generation of Vehicles, and DOE (DOE, 2010b; Snyder, 2012). These technical targets have played an important role in the development of battery technology beyond their use in various funding solicitations, which include DOE and USABC funding opportunity announcements and requests for proposals. These performance and cost criteria, goals, and targets have guided the industry in the development of technologies and products for electric drive vehicle applications.

Unfortunately, the technical targets for various applications crafted at various times over the past two decades are generally not consistent with one another in format or assumptions. Several key targets are in urgent need of revision. Most notably, the Goals for Advanced Batteries for BEVs have not been revised since their release in 1993. The technical targets for power-assist HEVs are more than a decade old. In particular, the BEV cost targets are no longer consistent with the changed factors that govern economic competitiveness, especially fuel costs but also the anticipated costs of future high-technology ICE vehicles that provide a benchmark. PHEV battery goals do not include targets for PHEVs with an all-electric range. (The targeted PHEVs with an equivalent electric range of 10 to 40 miles do not have sufficient power at 38 to 50 kW for any significant all-electric range but are designed for blended operation only.) Assumptions in the derivation of targets are generally not provided. There are no formal targets for electrochemical energy storage systems for fuel cell hybrid vehicles. There are inconsistencies in the criteria and even units (watts per kilogram for BEV batteries; watts and kilograms for HEV batteries). Production volumes on which cost projections are based are not consistent, nor are they consistent with the production volumes assumed for fuel cell vehicle cost projections.

It is time to take advantage of the past two decades of substantial progress, experience, and learning about electric drive vehicle applications to start over and develop a technically sound and consistent set of technical targets for electrochemical energy storage systems aimed at the key applications under development:

- Hybrid Electric Vehicles
    - Stop-start micro HEVs
    - Mild HEVs
    - Full HEVs
    - PHEVs, both blended and all-electric range types
- Battery Electric Vehicles
    - Commuter BEVs (<100 mile range)
    - Touring BEVs (300 mile range)
- Fuel Cell Hybrid Electric Vehicles

Assessment of Progress and Key Achievements

The electrochemical energy storage technology program has been a very comprehensive program aimed at all light-duty electric drive vehicle applications including HEVs, PHEVs, BEVs, and HFCVs. Projects aimed at these applications covered a wide scope, including battery development; applied battery research; exploratory materials research; and testing, analysis, and design. They ranged from basic materials development to battery systems development. Due in part to excellent progress toward goals for high-power batteries, the focus of battery development activities since the Phase 3 NRC (2010) review has shifted to high-energy batteries for PHEVs and BEVs. This is responsive to the recommendation in the NRC (2010) Phase 3 review and supports President Obama's call for 1 million PHEVs by 2015.

Substantial progress has been achieved relative to the key performance and cost targets, including energy density, power, cycle and calendar life, and cost of Li-ion batteries. A special focus was placed on developing lower-cost technologies, with a key strategy being the development of higher-energy-density materials, cells, and systems that could reduce materials costs. In particular, higher-energy-density anodes and cathodes for Li-ion batteries and materials enabling higher-voltage operation were developed to increase cell energy density and to lower materials costs. This approach yields great promise of meeting PHEV energy density and cost targets this decade. There is also a realization that even more substantial improvements will be needed to meet BEV energy density and cost targets. Thus, exploratory R&D is now being performed toward lithium metal and lithium air battery concepts.

General U.S. DRIVE Partnership achievements in electrochemical energy storage (DOE, 2012b) include the following:

- Cost reduction of Li-ion PHEV battery technology, with $650/kWh feasible at 100,000 packs per year production volumes and on track for meeting the $300/kWh goal this decade.[19]
- High-energy-density cathode material licensed to General Motors, LG Chem Ltd., BASF, Toda, and Envia Systems.
- Lifetime of Li-ion batteries extended to 10 to 15 years and/or 3,000 to 5,000 deep cycles for some technologies on test by USABC at U.S. national laboratories.
- Performance and life and safety targets met for HEV batteries, and significant cost reduction toward targets accomplished.

Specific highlights from U.S. DRIVE R&D programs (U.S. DRIVE, 2011; FCFP, 2011) include the following:

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[19] D. Howell, Department of Energy, and R. Elder, Chrysler, "Electrochemical Energy Storage Technical Team (EEST)," presentation to the committee, January 26, 2012, Washington, D.C.

- New prismatic cell and system technology based on Li-ion NMC (nickel-managese-cobalt) chemistry developed by Johnson Controls demonstrated 40 percent volumetric energy density improvement and 13 percent cost reduction. PHEV hardware deliverables in this USABC program also met other performance, safety, and life requirements according to tests and projections.
- High-specific-energy cathodes developed by Envia Systems using Argonne National Laboratory-patented technology achieved greater than 200 Wh/kg in a 20-Ah PHEV Li-ion cell delivered to USABC. A record-setting 400 Wh/kg was achieved in a prototype with a silicon-carbon anode under development in an ARPA-E program. Work continues to move this promising technology ahead toward meeting cycle-life and calendar-life targets.
- New inorganic-filled separators developed by Entek International LLC demonstrated improved safety performance as well as improved low-temperature power and life performance. This USABC development offers potential cost reduction through the use of smaller batteries that can meet lifetime performance requirements.
- Advanced Gen 2 NMC (nickel-manganese-cobalt) mixed oxide PHEV cathode material developed by 3M lowered material costs 15 percent while increasing specific capacity 5 to 10 percent with thermal stability and cycle-life performance comparable to Gen 1 materials.
- An electrolyte additive developed by the Army Research Laboratory significantly improves the high-voltage stability of 4.8-V lithium cobalt phosphate cathodes, which are capable of providing 40 percent higher energy density than commercially available lithium iron phosphate cathodes.
- High-voltage (4.8 V) cathodes composed of nickel-manganese spinel oxides doped with chromium developed by PNNL exhibited stable cycle performance through the use of LiBOB (lithium bis[oxatlato] borate) electrolyte additive.
- Silicon-based anode technology developed by 3M provided for a 15 to 20 percent increase in an Li-ion cell energy density with a cycle-life capability of hundreds of cycles and is now being commercialized.
- A multiscale, multidimensional model framework developed by NREL was used to initiate programs in multiphysics battery modeling to provide computer-aided engineering tools to the Li-ion battery industry.

Significant Barriers and Issues

The most serious barrier in the area of electrochemical energy storage is the high cost of batteries, which generally comprises the highest cost component of the electric propulsion system, with the exception of fuel cell systems. The cost targets for electric drive vehicles[20] are as follows:

- $125/kWh for battery electric vehicles (DOE target for 2020),
- $300/kWh for plug-in hybrid electric vehicles (DOE target for 2015), and
- $20/kW for hybrid electric vehicles (DOE target for 2010).

None of these targets aimed at widespread commercialization has been met. HEV battery costs are still 50 percent over target, and the consequent cost premiums for HEVs have clearly limited the market share that these vehicles have achieved. The PHEV battery high-volume cost feasibility is currently double the target. BEV battery costs exceed targets by a factor of four or more, generally making battery electric vehicles with a range of more than 100 miles unaffordable.

The second most serious barrier is the performance gap with respect to energy density for BEV applications. On a systems level, the gravimetric energy density is about half of the target. BEV battery cost and energy density are highly correlated, since higher specific energy systems will require fewer materials, reducing materials costs, and they will be smaller, reducing packaging costs.

There has been great progress in recent years in overcoming safety issues with Li-ion batteries, through the use of intrinsically safer materials and through design for safety on a systems level. However, as the 2011 incidents surrounding Chevy Volt PHEVs after crash testing indicate, continued vigilance with safety development is essential. Additionally, as higher-energy-density battery systems are developed, further diligence is needed owing to the intrinsic tendency for increased hazard with higher energy densities.

The technology barriers for Li-ion batteries are well understood. Barriers for more exotic new technologies with higher theoretical specific energy are now being uncovered and will become clearer as development advances. For example, issues with lithium air batteries now include low power, poor efficiency, short cycle life, and system complexities approaching those of fuel cells.

Response to Phase 3 Recommendations

> ***NRC Phase 3 Recommendation 3-16.*** *The Partnership should revisit and modify, as necessary, the goals and targets for battery electric vehicles in view of the changing market conditions and improvements in technologies.* [NRC, 2010, p. 93.]

This recommendation for the revision of targets for BEVs was not acted on. The official targets remain those developed 20 years ago. With the renewed activities

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[20] D. Howell, Department of Energy, and R. Elder, Chrysler, "Electrochemical Energy Storage Technical Team (EEST)," presentation to the committee, January 26, 2012, Washington, D.C.

aimed at BEVs, including embryonic commercial programs with the Tesla Roadster and the Nissan Leaf, it is now even more urgent to revisit this matter. The revised goals and targets should be consistent with recent USABC targets for PHEV batteries and HEV batteries and should incorporate what has been learned in the past two decades. In addition to a long-term goal aimed at a 300-mile range, it would be useful to establish targets for 100-mile-range commuters. These vehicles, which have sufficient range to meet the needs of most U.S. commuters, are now starting to be introduced into the market. Furthermore, additional diligent efforts are needed to review targets for other applications and to provide a consistent and up-to-date set of technical targets across all key electric drive vehicle applications.

> ***NRC Phase 3 Recommendation 3-17.*** *The Partnership should significantly intensify its efforts to develop improved materials and systems for high-energy batteries for both plug-in electric vehicles and battery electric vehicles.* [NRC, 2010, p. 93.]

Activities into the development of high-energy batteries were intensified as recommended. Significant progress has helped enable the embryonic introduction of PHEVs and the reintroduction of BEVs, albeit with limited range.

> ***NRC Phase 3 Recommendation 3-18.*** *The Partnership should conduct a study to determine the cost of recycling batteries and the potential savings from recycled materials. A research program on improved processes for recycling advanced batteries should be initiated in order to reduce the cost of the processes and recover useful materials and to reduce potentially hazardous toxic waste and, if necessary, to explore and develop new processes that preserve and recycle a much larger portion of the battery values.* [NRC, 2010, p. 93.]

In response to the recommendation for a study on recycling batteries, U.S. DRIVE referred to an analysis by Argonne National Laboratory showing that recycling of Li-ion batteries can mitigate material supply issues and provide cost savings from recycled materials (Gaines, 2011). Battery recycling is also being studied in an ongoing effort by USCAR and remains an area of interest for the Vehicle Technologies Program of DOE. Additionally, with ARRA funds, DOE has supported Toxco in a cost-shared project for construction of a Li-ion battery recycling facility. Further process development for recycling Li-ion batteries is needed, as well as full-life-cycle assessment studies for all environmental externalities (see Chapter 2, Recommendation 2-10).

Appropriate Federal Role

Clearly, the long-term R&D aimed at fundamental discoveries on precompetitive technology development, as in the Applied Battery Research and Exploratory

Battery Research programs as well as the related activities funded through the Office of Basic Energy Sciences and ARPA-E, is completely appropriate for federal funding. Little of this work would be performed by private industry without government support.

The Battery Development effort of USABC is of a more near-term nature and benefits specific companies as well as the automotive OEMs, as hardware is developed that can be translated into products in a relatively short time frame. However, developers are typically required to provide a 50 percent cost share. Thus, it is a reasonable role for the government to assist companies in taking the risk to develop technologies that show promise for commercial success. The cost-share provision helps focus on the development of viable technologies.

Although not part of the U.S. DRIVE Partnership and the committee's review, cost-shared programs were funded by the ARRA of 2009 for the building of battery plants to jump-start the Li-ion battery industry in the United States. A large investment of $1.5 billion was made in the manufacturing of Li-ion battery technologies developed through the U.S. DRIVE Partnership. The knowledge in manufacturing processes and product cost reduction gained from these programs will be invaluable.

Recommendations

Improvements in high-energy batteries as well as in high-power batteries and supercapacitors will be of benefit for many advanced vehicles.

Recommendation 3-12. While continuing mainstream efforts to increase energy density and reduce the cost of high-energy batteries for BEV and HEV applications, the U.S. DRIVE Partnership should intensify its development of high-power batteries and supercapacitors as such technology impacts all types of hybrid vehicles (HEVs, PHEVs, and HFCVs). It should also more closely integrate its efforts with other DOE offices and agencies to investigate new high-energy electrochemical couples for BEV applications.

The U.S. DRIVE Partnership technical targets for electrochemical energy storage systems are largely outdated and contain some significant inconsistencies and unclear constructions. Notably, the USABC targets for BEV batteries are more than 20 years old.

Recommendation 3-13. The USABC targets for BEV batteries are more than 20 years old and should be revised, as also recommended in the NRC's Phase 3 review. U.S. DRIVE should also undertake a diligent effort to develop a consistent set of technical targets across the key electric drive vehicle applications.

ELECTRIC PROPULSION AND ELECTRICAL SYSTEMS

Introduction and Background

The mission of the U.S. DRIVE Partnership's electric propulsion and electrical systems effort is to "develop technologies to enable large market penetration of electric drive vehicles."[21] Thus, the accomplishments of this activity will impact all hybrid electric vehicles, mild or full hybrid, plug-in hybrid electric vehicles and extended-range electric vehicles (EREVs), battery electric vehicles, and hydrogen fuel cell (electric) vehicles. The architectures for these vehicles were schematically illustrated in Figures 3-6 through 3-10 in the NRC (2010, pp. 95-97) Phase 3 report and will not be repeated here. Since the Phase 3 review, there has been tremendous interest worldwide in electric propulsion and hybrid vehicles, with several new models of HEVs, PHEVs, EREVs, and BEVs introduced recently. This is due to a general awareness and to increased regulation to reduce fuel consumption and greenhouse gas emissions. Thus, there is significant development of electric motors and power electronics in private industry in addition to DOE-funded activities.

The electric propulsion development FY 2012 budget of $28.8 million is subdivided into four major subsections with the following associated budgets: (1) power electronics, $10 million; (2) electric motors, $7 million; (3) thermal management, $6 million; and (4) traction drive systems, $3 million. Another $3 million is unassigned as of this writing and is for new solicitations. The FY 2012 amount represents a small increase from $22.2 million spent in FY 2011 and FY 2010. The electrical propulsion development was also enhanced by ARRA funding in 2009[22] to accelerate the development of U.S. manufacturing of electric drive components and by several ARPA-E projects on charging systems and electric motors. In particular, 14 projects constitute ARPA-E REACT[23] (Rare Earth Alternatives in Critical Technologies) for the development of cost-effective alternatives to rare-earth, magnetic materials used in electric motors. These activities are not under the U.S. DRIVE Partnership but do reflect the importance of the electric propulsion development effort.

The general objective of the program is to reduce the cost, weight, and volume of the various components and systems for electric propulsion. Since these systems have also been investigated for non-transportation applications, it is important that the electrical and electronics technical team be fully aware of the state of the art of the various technologies. Also it might be useful if the technical team conducted a careful analysis to determine that the investigation is precompetitive and involves breakthrough technologies relevant for U.S. DRIVE.

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[21] J.Czubay, General Motors, and S. Rogers, Department of Energy, "Electrical and Electronics Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

[22] See http://apps1.eere.energy.gov/news/daily.cfm/hp_news_id=192http:/apps1.eere.energy.gov/news/daily.cfm/hp_news_id=192.

[23] See http://arpa-e.energy.gov/ProgramsProjects/REACT.aspx.

At the present time, the power electronics and electrical machine costs relative to the rest of the drive system depend on the type of drive. For mild HEVs the costs are relatively small, but as the power increases with full HEVs and PHEVs, the cost increases. EREVs, such as the Chevrolet Volt, and BEVs and HFCVs would be the most costly. Thus reducing the cost, weight, and volume is an important and worthwhile objective, and the funds allocated for this activity are appropriate.

Current Status Versus Targets

The electric propulsion and electrical systems targets have been met for 2010, including the cost, weight, and volume targets for the electric motor, power electronics, and traction drive system efficiency. Progress is continuing on the 2015 and 2020 targets, and preliminary data suggest that a General Motors (GM) integrated traction drive system meets the weight and volume target but not the efficiency or cost target for 2015. Since all of these properties are interrelated, meeting just some of the targets may not be sufficient. Also, several requirements for individual components emphasize performance at peak values only, which may be valuable for determining progress, but the final performance can only be judged on the basis of its effect on fuel economy—that is, performance of the component over the standardized driving cycles (city and highway).

Assessment of Progress and Key Achievements

The main achievement in the electric propulsion and electrical systems area was that of meeting all the 2010 and some of the 2015 targets with the GM and Delphi/GE traction drive and electric motor system. In addition, several important and promising initiatives are underway that should result in reduction of cost, size, and weight in power electronics, electric motors, thermal management, and traction drive systems.

Power Electronics

The program involving power electronics has several projects on materials, components, and design topology for switches and circuits. Thin-film capacitors that can operate at higher temperatures have been developed; however, these have not been commercialized. Switches have been designed using wide-band-gap semiconductors, such as silicon carbide (SiC); however, such materials are very expensive, and the Partnership should leverage industry efforts to reduce the cost of manufacturing and should determine how best to utilize these in power electronics for vehicular applications. Projects on inverter topology[24] are being funded

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[24] The term “inverter topology” is used to describe the arrangement of semiconductor switches, diodes, coils, and capacitors.

in this program; however, there is no significant effort to benchmark the target improvements of these projects over inverters employed in production vehicles that use electric propulsion.

A proposed project is investigating the use of the same power switching devices for both the charger and the inverter. AC Propulsion is already marketing such a system, and it is being used in the Tesla and BMW Mini electric vehicles. It is hoped that the proposed project endeavors to improve on these production systems.

Electric Motors

The cost of rare earths used for permanent magnets has increased substantially, some by as much as an order of magnitude,[25] in the past few years, and the Partnership has initiated projects to develop magnets without, or with a minimum of, rare earths. Extensive research on this subject is being done at the national laboratories. It is too early to evaluate the results, but this activity should be encouraged. Recently Mitsubishi has claimed success with magnet alloys with 1 to 4 percent rare-earth content with performance comparable to the magnets in the Prius, which contain approximately 10 percent rare-earth.[26]

There is also a need for improved soft magnetic materials. Soft magnetic materials, which are used in motors, inductors, and transformers with higher permeability, high flux density, and low loss, are needed. The standard for decades has been high-silicon steel with a maximum of 4 percent Si. More recently a Japanese company[27] has developed a new process for making 6.5 percent Si, which will have lower loss but perhaps lower peak flux density. The suitability of this development needs to be determined.

The program is also investigating new permanent-magnet motor designs. A possible design uses open slots to facilitate the insertion of formed coils, reducing costs and reducing resistance loss but increasing eddy current losses on the magnets. It is hoped that this and other such projects bring about improvements over production motors used in hybrid vehicles on the road. In the Phase 3 report (NRC, 2010), it was recommended that induction motors for electric propulsion be investigated. Several hybrid vehicles on the road, such as the GM Buick LaCrosse, Tesla, and BMW, are using induction motors. Thus it may be worthwhile to compare induction and permanent-magnet motors to determine the relative efficiency and cost trade-offs for the two systems. Switched reluctance motors are also being investigated; however, acoustical noise continues to be an issue with this design.

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[25] See, for example, http://www.ft.com/intl/cms/s/0/751cab5a-87b8-11e0-a6de-00144feabdc0.html#axzz28AaO9ofv.

[26] SAE, 2012, Powertrain Electric Motors Symposium for Electric and Hybrid Vehicles (April 20, 2012).

[27] JFE Steel Hibiya Kokusai Building, 2-3 Uchisaiwaicho 2-chome, Chiyodaku, Tokyo 100-0011, Japan; see http://www.jfe-steel.co.jp/en/.

On the other hand, ASEA-Brown Boveri claims that a synchronous reluctance motor has a better efficiency than an induction motor at smaller sizes.

Thermal Management

Heat removal from the silicon chip is a key determinant of the efficiency and size of the power electronics; thus thermal management plays an important role in meeting the program targets. Furthermore, matching differential expansion between the silicon chip and the (typically) aluminum heat sink is a tough problem, especially over the temperature range of –40°C to 200°C. There are many ways to minimize the thermal resistance from the silicon to the heat sink. One alternative is to use only aluminum and no copper plates to remove the heat. Other techniques consist of using direct sintering or double-sided cooling. The Oak Ridge National Laboratory claims to build a small, high-efficiency, planar bonded power electronic module for improved thermal management (Olszewski, 2011).[28] A study to evaluate and compare the various alternative techniques and their relative merit to production units would be appropriate.

The Nissan Leaf battery is air cooled, and other vehicles use liquid cooling. For example, the Volt uses a 50/50 mix of ethylene glycol for cooling the battery and possibly the inverter, whereas other vehicles use transformer oil.

Traction Drive System

The emphasis on the traction drive system in this program seems to be on components rather than on investigating the traction drive as a system. In fact, a thorough systems analysis of the traction drive may result in more optimized targets for the necessary components. Such an analysis is highly encouraged. For example, it may be possible to trade off the cost of improving the motor efficiency versus increased battery cost. The electric motor efficiency is targeted to be 95 percent or higher over a range of torque of 20 to 100 percent and over speeds of 10 to 100 percent. Such high efficiency over such a wide range of load seems overly ambitious. It may be more cost-effective to improve the battery performance by 2 percent compared to the cost of raising the drive efficiency from 93 percent to 95 percent.

Also, there seems to be little work on “less costly mild hybrids.” Recently GM started selling the Buick LaCrosse Hybrid (Hawkins et al., 2012) with great improvements in the Environmental Protection Agency’s fuel economy (in miles per gallon) ratings.[29] This remarkable result was achieved by a systems approach in which hybridization includes aggressive fuel cutoff during decelerations and stop-start.

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[28] J. Czubay, General Motors, and S. Rogers, Department of Energy, “Electrical and Electronics Technical Team,” presentation to the committee, January 26, 2012, Washington, D.C.

[29] See http://www.fueleconomy.gov/feg/hybridCompare.jsp.

Significant Barriers and Issues

Although electric machines and power electronics have been developed for many years for a variety of commercial applications, there are significant barriers to their utilization in electric drive vehicles, including BEVs, HEVs, PHEVs, and HFCVs. Barriers include inadequate efficiency and inadequate volumetric and gravimetric power density, and, most importantly, excessive costs.

As discussed, a significant issue with this program is a lack of a thorough systems analysis of the complete traction drive system. Such an analysis not only would guide the program to which activity will provide the best results, but also would provide more optimized targets for efficiency, weight, volume, and cost for the various components constituting the system. Ideally, this should also include the battery, fuel cell, and internal combustion engine, so that the whole system can be optimized, and would involve separate analysis and targets for HEVs, PHEVs, BEVs, and HFCVs.

As noted, significant improvements in various components and systems are being made at the national laboratories in this program. However, not much of this effort is finding its way to commercial applications. Also, establishing a supplier base for the large number of components involved in building an electrical drive system is warranted.

Response to Recommendations from Phase 3 Review

> ***NRC Phase 3 Recommendation 3-19.*** *The Partnership should continue to focus on activities to reduce the cost, size, and losses in the power electronics and electrical machines.* [NRC, 2010, p. 105.]

U.S. DRIVE seems to have pursued this recommendation. Prime examples are the GM, Delphi, and GE contracts that have improved on the state of the art.

> ***NRC Phase 3 Recommendation 3-20.*** *The Partnership should conduct a project to evaluate the effect of battery charging on lithium-ion battery packs as a function of the cell chemistries, cell geometries, and configurations in the pack; battery string voltages; and numbers of parallel strings. A standardized method for these evaluations should be developed to ensure the safety of battery packs during vehicle operation as well as during plug-in charging.* [NRC, 2010, p. 105.]

The committee believes that this recommendation needs more attention. There is no evidence that the Partnership considered how high-rate charging affects the life of the battery.[30] This issue needs to be addressed together with the

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[30] The following inaccurate and factually wrong sentence was removed from the report: “It is particularly surprising that nothing seems to have been done regarding safety even after the fires developed on the Volt in mid-2011.”

electrochemical energy storage team and affects not only the charging regimen but also the monitoring and equalizing of the voltage of the cells. The role of the electrical and electronics technical team would be to specify the charging rates; presumably it can meet the need. Lithium-ion batteries have a history of causing fires in several instances. In addition to safety, there is a need to worry about battery life, especially with "fast charging" at 440 V. The committee believes that continued work in this area is important and that the U.S. DRIVE Partnership should revisit Phase 3 (NRC, 2010), Recommendation 3-20.

> ***NRC Phase 3 Recommendation 3-21.*** *The Partnership should consider conducting a project to investigate induction motors as replacements for the permanent-magnet motors now almost universally used for electric propulsion.* [NRC, 2010, p. 105.]

U.S. DRIVE seems to have relied on preliminary findings from an ongoing DOE motor assessment indicating that induction motors will not meet its targets.[31] This is interesting in that a mild hybrid vehicle (2012 Buick LaCrosse using the eAssist mild hybrid system) on sale by one of the Partnership's partners demonstrated great improvement in fuel consumption, as discussed above. Clearly other factors contributed, but induction motors will meet some of the targets. Also, one of the new partners, Tesla, uses an induction motor in its vehicles. BMW also uses induction motors in some of its BEVs.

Appropriateness of Federal Funding

There is tremendous interest in electric propulsion worldwide, and a great deal of money is spent on improving the state of the art. However, HFCVs, BEVs, PHEVs, and even HEVs are unlikely to capture a significant share of the market unless dramatic improvements take place in all elements of the drivetrain. In addition to the battery and fuel cell systems, which are discussed in other sections of this report, the cost, volume, and weight of power electronics and motors need significant breakthroughs. The Partnership is focusing on these three areas, which are interdependent. For example, better cooling of electronics reduces not only cost but also volume and weight; integrating the motor and electronics reduces not only cost but also volume; replacing rare-earth magnet materials has the potential of significantly reducing cost, although volume and weight may go up. Most of the funding goes to national laboratories, which will produce fresh thinking that would complement industry efforts, while the Partnership combines the best thinking of both. The fact that the electric propulsion components are used for all types of electric drive vehicles makes this a very strategically attractive R&D

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[31] J. Czubay, General Motors, and S. Rogers, Department of Energy, "Electrical and Electronics Technical Team," presentation to the committee, January 26, 2012, Washington, D.C.

investment and, in the committee's view, the government has an appropriate role in helping with the introduction of electric propulsion and providing the United States with leadership.

Recommendations

Recommendation 3-14. The U.S. DRIVE Partnership should leverage the various investigations on wide-band-gap materials such as silicon carbide (SiC) and should determine how best to utilize these in power electronics for vehicular applications.

Recommendation 3-15. The U.S. DRIVE Partnership should determine the potential and limitations of designing motors with permanent-magnet materials using less rare earth metal.

Recommendation 3-16. The U.S. DRIVE Partnership should make a comprehensive assessment of the various methods available (some of these are discussed in the section titled "Thermal Management" in this chapter) to reduce the thermal resistance between the chip and the heat sink and establish their relative value to existing techniques in production vehicles.

MATERIALS

Goals and Challenges

A critical component of any automotive manufacturer's strategy to reduce fuel consumption and meet increasingly stringent Corporate Average Fuel Economy (CAFE) standards and greenhouse gas emissions requirements is to reduce vehicle weight. For example, DOE has estimated that a 10 percent reduction in vehicle weight can result in up to a 6 to 8 percent improvement in fuel economy. Consequently, the U.S. DRIVE materials technical team (MTT), like the FreedomCAR and Fuel Partnership before it, has adopted a stretch goal of 50 percent reduction in vehicle weight (versus 2002 comparable vehicles) *with equal affordability* (emphasis added). Previous committees (NRC, 2008, 2010) found this goal unrealistic, and it remains so today.

Nevertheless, reducing vehicle weight *is* important, and doing so at the least incremental cost, while challenging, is worthy of pursuit, since achieving the 50 percent goal would result in up to a 35 percent fuel economy improvement. The DOE has developed a roadmap for a 30 percent weight reduction by 2025, which, if achieved, would result in up to a 21 percent fuel economy improvement.

One factor that potentially assists with the task of major weight reductions is that of mass decompounding. That is, a reduction of weight in basic vehicle structure permits secondary weight reduction in brakes, suspension, power train, and other components. The materials technical team has estimated that each 1.0 lb of primary weight reduction may enable 1.0 to 1.5 lb of secondary weight reduction, provided that the entire vehicle can be redesigned to capture this opportunity. Nevertheless, large-scale weight reduction is an extremely challenging task, particularly since the addition of enhanced fuel-efficiency systems such as electrification results in the opposite effect, namely, mass *compounding*.

Broadly speaking, there are three obstacles to achieving the Partnership's stated stretch goals regarding vehicle weight: increasing vehicle content, maintaining structural integrity, and managing cost.

- A 2011 Massachusetts Institute of Technology study (Zoepf, 2011) found that average passenger-car weight had increased by greater than 11 percent, or 160 kg, since 1990, despite the base car weight remaining unchanged. The entire weight increase was attributable to increasing comfort and convenience content and to added safety features and requirements. The pressure to keep adding feature content and more safety features will undoubtedly continue, in conflict with the need to reduce weight. Furthermore, the enhanced electrification of vehicles, while improving inherent fuel efficiency, adds considerable mass in batteries, motors, electronics, cooling, and so on, which must all be offset, including the mass compounding effect noted above, to yield the greatest fuel consumption benefits.
- Compliance with the full suite of Federal Motor Vehicle Safety Standards provides confidence in the overall safety performance of a vehicle, but it becomes increasingly challenging as weight is reduced. This has led to increased use of sophisticated structural analysis tools and demand for stronger, lighter materials such as high-strength steels and carbon fiber. This trend can only accelerate in the future.
- Cost is arguably the greatest challenge of the three: a detailed analysis in the NRC (2010) Phase 3 report illustrated both the high cost of weight reduction and the extent to which the reduction in fuel consumption can offset part of the cost to the ultimate consumer. However, the offset in fuel cost is only a fraction of the material cost penalty, and furthermore, much of the proverbial "low hanging fruit" has been harvested already.

In light of these challenges, having the Partnership's activities focused as they are on enabling advanced high-strength lightweight materials and reducing their cost appears to be appropriate, even if the ultimate stretch goal is unrealistic.

Achievements

In the materials area, the Partnership listed eight areas of major achievement in its presentations to the committee on January 26, 2012.[32] These were as follows:

- Completed design and manufacturability assessment of a *magnesium front-end structure*.
- Completed design, tooling, fabrication, and testing of a *one-piece composite underbody,* saving 11.3 kg.
- Optimized engineering and manufacturing processes for *advanced high-strength steel (AHSS).*
- Developed a process for *warm forming of aluminum and magnesium sheet.*
- Enhanced the *formability of aluminum at room temperature.*
- Demonstrated a conversion technique for *low-cost textile precursor for carbon fiber.*
- *Improved performance of AHSS welds.*
- Developed a unique process for producing *low-cost highly ductile magnesium sheet.*

Response to Recommendations from the Phase 3 Review

Three recommendations on materials were made in the NRC Phase 3 report (NRC, 2010, pp. 108-109). The Partnership responses are shown below as "Updates."

> ***NRC Phase 3 Recommendation 3-22.*** *The materials technical team should develop a systems-analysis methodology to determine the currently most cost-effective way for achieving a 50 percent weight reduction for hybrid and fuel cell vehicles. The materials team needs to evaluate how the cost penalty changes as a function of the percent weight reduction, assuming that the most effective mix of materials is used at each step in the weight-reduction process. The analysis should be updated on a regular basis as the cost structures change as a result of process research breakthroughs and commercial developments*. [NRC, 2010, p. 108.]

Updates: DOE FY 2011 solicitation results for the multimaterial vehicle car (50 percent lighter than a midsized vehicle, design, build, and validate):

- Award to Vehma (Magna International)—project started in November 2011.

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[32] M. Zaluzec, Ford Motor Company, and C. Schutte, Department of Energy, "Materials Technical Team (MTT)," presentation to the committee, January 26, 2012, Washington, D.C.

- Cost analysis for multimaterial vehicle with a systematic approach is in process at the Oak Ridge National Laboratory.

NRC Phase 3 Recommendation 3-23. *The magnesium castings study is completed, and no further technical effort is anticipated by the Partnership as recommended in the Phase 2 report. However, magnesium castings should be considered in completing the cost reduction recommendations listed above.* [NRC, 2010, p. 109.]

Updates:

- DOE award to MOxST, Inc., for a clean and low-cost domestic supply of magnesium (Mg). If successful, this technology will introduce a lower-cost feedstock for alloy production and die casting.
- DOE award to United States Automotive Materials Partnership (USAMP) on Magnesium Intensive Front End, which includes a focus on the characterization, optimization, and production of Mg die cast structural components.
- Cooperative Research and Development Agreement project involving the Pacific Northwest National Laboratory, Ford Motor Company, University of Michigan, and MagTech (die casting supplier) to develop and validate mechanistic-based ductility models for Mg die castings. This will provide a better understanding of how die-casting characteristics affect ductility, in turn providing insight for methods to improve ductility.

NRC Phase 3 Recommendation 3-24. *Methods for the recycling of carbon-reinforced composites need to be developed.* [NRC, 2010, p. 109.]

Updates: DOE cofunding of Small Business Innovation Research work with Materials Innovation Technologies (Fletcher, North Carolina) to research low-cost carbon-fiber composite manufacturing using recycled aerospace carbon-fiber.

Other global recycling efforts identified are as follows:

- Nottingham University, United Kingdom: Fluidised Bed, Supercritical Fluids, Microwave;
- Adherent Technologies, New Mexico, United States: Batch Thermo-chemical;
- Valley Stade Consortium, Germany: Batch Pyrolysis;
- Wells Specialty Products, Texas, United States: Fluidized Bed;
- Ruag, Switzerland;
- Firebird Advanced Materials, North Carolina, United States: Microwave; and
- Milled Carbon, United Kingdom: Continuous Pyrolysis.

Discussion and Recommendations

As noted earlier, weight reduction is a crucial part of any balanced approach to achieving aggressive fuel consumption targets and will undoubtedly entail enhanced computational methods and widespread materials substitution. The work being performed under the auspices of the Partnership appears to be properly focused on relevant initiatives.

Although these initiatives appear relevant, the committee questions whether they all satisfy the criteria of high-risk, precompetitive research judged appropriate for federal involvement. Competition has raged among the steel, aluminum, and composites automotive supply base for many years in an effort to achieve low-cost weight reduction via materials substitution, and the aluminum, magnesium, high-strength steel, and composites content of production vehicles has been steadily rising for more than 20 years. Furthermore, numerous vehicle demonstration projects have been conducted in the past, both by materials trade associations and by industry consortia, some of which were sponsored by DOE.

As noted in Chapter 2, the committee applauds the appointment by each technical team of an associate member. However, the MTT has selected as its associate member a manufacturer of aluminum truck bodies; although the company no doubt is competent, this selection would seem to add little in the area of greatest need, namely, long-term high-risk research into low-cost lightweight alternative materials. It might be productive for MTT to consider adding another associate member with this type of expertise. Phase 3 Recommendation 3-22 emphasized the need for *systems analysis* focusing on the most *cost-effective* way to achieve a 50 percent weight reduction. While the analytical approach in process at ORNL is responsive to that task, it is less clear what value the $10 million award (over 4 years) to Vehma to build another prototype multimaterial vehicle offers, especially considering that the award abstract does not even mention cost.

Phase 3 Recommendation 3-23 reiterated the Phase 2 recommendation (NRC, 2008, p. 9) and essentially anticipated no further work on magnesium, other than inclusion in the analytical optimization process. The Partnership nevertheless listed in its response several continuing Mg projects within the 67 percent of DOE's FY 2012 budget that is devoted to metals development.

Phase 3 Recommendation 3-24 urged the development of methods to recycle carbon-fiber composites. The Partnership is devoting 18 percent of its FY 2012 Lightweight Materials budget to carbon-fiber projects, including recycling. Although this is responsive to the committee recommendation, it can be argued that carbon fiber offers perhaps the greatest opportunity for weight reduction while maintaining structural integrity, and hence the huge challenge of doing so at low cost could deserve a greater share of the materials budget.

While increased emphasis on low-cost carbon fiber would be desirable, the committee continues to believe that much of the MTT work on light metals and materials substitution demonstrations is not precompetitive and would be best performed by the private sector. Funding currently allocated to these activities could well be used more effectively by other technical teams or on materials research needs identified by those other teams.

Recommendation 3-17. The Partnership should expand its current work on low-cost carbon-fiber precursors, manufacturing, and recycling. This work could also potentially help to reduce the cost of high-pressure hydrogen storage tanks.

Recommendation 3-18. The materials technical team should expand its outreach to the other technical teams to determine the highest-priority collective Partnership needs, and the team should then reassess its research portfolio accordingly. Any necessary reallocation of resources could be enabled by delegating some of the highly competitive metals development work to the private sector.

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4

Hydrogen, Alternative Fuels, and Electricity

The U.S. DRIVE Partnership is focused on reducing petroleum consumption and greenhouse gas (GHG) emissions by employing three power systems: hydrogen fuel cell vehicles (HFCVs), advanced combustion engines, and plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) using electricity. Hydrogen is an energy carrier produced from a variety of energy sources, but at present it is mostly produced from natural gas. Biofuels, energy carriers for solar energy and thus renewable fuels, are produced from a variety of biological sources, including plant materials and algae. Electricity is an energy carrier that is generated from a variety of sources today, but in the United States mostly from coal and natural gas. This chapter reviews the programs relating to hydrogen that are under the U.S. DRIVE Partnership effort. (Budget information was provided by U.S. DRIVE and the U.S. Department of Energy [DOE] in response to questions from the committee.) The chapter also includes an overview of issues relating to the Partnership's role in biofuels, natural gas, and electricity for PHEVs and BEVs.

FUEL PATHWAYS

Strategic Input Needed from Executive Steering Group

One of the challenges of the U.S. DRIVE Partnership is to have critical fuels and vehicle technologies both commercially ready so that the required fuels can be in place when vehicles with advanced technologies become available in the marketplace. The Partnership is focused on having advanced vehicle technologies with cost and performance comparable to those of conventional technologies by 2020, and so critical fuel technologies will also need to meet that time line.

The level of DOE funding in FY 2012 for the hydrogen production portion of the U.S. DRIVE Partnership will be 8.6 percent lower than the FY 2011 level, which was significantly reduced from FY 2009. Pressures to reduce expenditures are likely to have important impacts on program areas outside of U.S. DRIVE that provide important technology input. The Partnership is dependent on DOE's Office of Fossil Energy (FE) and Office of Basic Energy Sciences (BES), as well as the Biomass Program in the Office of Energy Efficiency and Renewable Energy (EERE), for technologies relating to hydrogen generation, biofuels, and electricity, all of which affect the U.S. DRIVE Partnership strategically.

The Fuel Cell Technologies Program (FCTP) has done an admirable job of coping with these changes and the uncertainty, and it has provided coordination links with programs in other parts of DOE. However, managing the various programs under U.S. DRIVE to ensure that the required fuel technologies will be available as new vehicle technologies emerge remains a challenge, and there is a compelling need to maximize the impact of funds spent toward completing critical fuels and vehicle programs at the same time. The Partnership has diligently involved its various technical teams to gain "user" input, but these teams have not provided overall guidance across all fuel categories. Given the changes that have taken place, the continuing environment of uncertainty, and the approaching dates for planned commercial readiness, the committee believes that U.S. DRIVE should seek strategic "user" input from its Executive Steering Group (ESG) on the program direction, focus, and timing to ensure that critical fuel technologies are available when needed.

Recommendation 4-1. The DOE should seek the strategic input of the Executive Steering Group (ESG) of U.S. DRIVE. The ESG could provide advice on all DOE fuel programs potentially critical to providing the fuel technologies needed in order for advanced vehicle technologies to achieve reductions in U.S. petroleum dependence and greenhouse gas emissions, and DOE should subsequently make appropriate program revisions to address user needs to the extent possible.

Hydrogen Fuel Pathways

In the United States today, hydrogen is a major industrial gas with an annual production and consumption, mostly from centralized natural gas reforming plants, of approximately 20 million metric tons (20 billion kg) (NHA, 2010).[1] A study of the transition to alternative transportation technologies (NRC, 2008, pp. 31-35) concluded that 2 million fuel-cell-powered vehicles would be the maximum practical number in 2020. Two million vehicles would increase hydrogen

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[1] The figure of approximately 20 million metric tons reported by the National Hydrogen Association (NHA, now called the Fuel Cell and Hydrogen Energy Association) includes hydrogen produced from merchant plants.

demand by about 2 percent[2] based on today's production, an increase that could be readily met in centralized plants by utilizing existing excess capacity or by building additional capacity. Thus, the issues during transition do not concern having enough hydrogen available overall but rather, having it available where needed at an acceptable cost and overall efficiency.

Three principal pathways appear feasible to meet the need: (1) transmission and distribution from centralized plants of gaseous hydrogen by tube trailer, (2) distribution of liquefied hydrogen by tanker, and (3) on-site generation of hydrogen at the fueling site using natural gas reforming or electrolysis of water. Hydrogen demand for transportation would thus be satisfied by combinations of centralized and on-site hydrogen production.

The "lighthouse scenario" is likely to play an important part initially in supplying needed hydrogen. In this scenario, widespread use of hydrogen fuel is encouraged in high-density cities and regions to achieve high market penetration in those areas and thus, it is hoped, a reduction in the cost of the fuel. These lighthouse areas would serve as a starting point for the development of a nationwide network. Such a system has already been proposed for Germany, and Honda is working in California on a similar approach.[3] In addition, the California Fuel Cell Partnership, with support from the University of California, Davis, has been actively pursuing this approach.[4] Needless to say, regulation could also play an important part in providing early hydrogen stations. A regulation being considered in California would require oil refiners to provide hydrogen stations on a schedule that meets the automotive original equipment manufacturers' (OEMs') projected introduction of hydrogen vehicles once the number reaches 10,000 (CARB, 2011). Considerable work remains to be done to identify pathway scenarios that fill the needs of specific market segments in the United States while minimizing cost and maximizing efficiency.

The hydrogen fuel/vehicle pathway integration effort is charged with looking across the full hydrogen supply chain from well (source) to tank for fuel cell vehicles and has been expanded to include the vehicle components, or life-cycle

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[2] This assumes that 5.6 kg of H_2 per tank yields a 400-mile range. If each hydrogen fuel cell vehicle travels 15,000 miles per year, then each vehicle would consume 210 kg per year. A fleet of 2 million would then consume 420 million kg of H_2 per year.

[3] Sasha Simon, Mercedes-Benz, "The Mercedes-Benz Hydrogen Roadmap," presentation to the NRC Committee on the Potential for Light-Duty Vehicle Technologies, 2010-2050: Costs, Barriers, Impacts and Timing, March 22, 2011, Washington, D.C.; R. Bienenfeld, Honda Motor Company, "Honda's Environmental Technologies Overview," presentation to the committee, June 5, 2012, Washington, D.C.

[4] "Incentivizing Hydrogen Infrastructural Investment. Phase 1: An Analysis of Cash Flow Support to Incentivize Early Stage Hydrogen Investment," June 2012, prepared by Energy Independence Now in conjunction with the California Fuel Cell Partnership Roadmap, available at http://www.einow.org/resources/reports.html, and "A California Road Map: Bringing Hydrogen Fuel Cell Vehicles to the Golden State," California Fuel Cell Partnership, July 2012, available at http://cafcp.org/sites/files/20120720_Roadmapv(Overview)_0.pdf.

analysis. The goal of this effort is to support the U.S. DRIVE Partnership in the identification and evaluation of implementation scenarios for fuel cell technology pathways in the transportation sector, both during the transition period and in the long term, by (1) analyzing issues associated with complete hydrogen production, distribution, and dispensing pathways; (2) commenting to the Partnership on methodologies for setting targets for integrated pathways and pathway components; (3) providing observations to the Partnership on needs and gaps in the hydrogen analysis program; and (4) enhancing the communication of analysis parameters and results so as to improve consistency and transparency in all analysis activities. All of this work is considered by the committee to be important and an appropriate use of federal funds.

This effort is overseen by the fuel pathway integration technical team (FPITT), with representation from DOE, four energy companies, and the National Renewable Energy Laboratory (NREL). The expertise of this group supports analysis efforts of the Partnership on fuel cell technology pathways, coordinating fuel activities with the vehicle systems analysis effort, recommending additional pathway analyses, providing input from industry on practical considerations, and acting as an honest broker for the information generated by other technical teams.

The Partnership continues to make significant and important progress toward understanding and preparing for a transition to hydrogen fuel. During the past 2 years, a methodology for documenting and reporting assumptions and data for well-to-wheels analysis has been developed and is available.[5] In addition, a methodology was developed for analyzing the optimal placement of central (large) hydrogen production facilities, and there was an evaluation of other industrial options and synergies for the use and supply of hydrogen, such as the coproduction of hydrogen from stationary fuel cells.

With guidance from a recently developed prioritized list of gaps and barriers, current efforts include an analysis of hydrogen fueling station costs during the early phase of hydrogen deployment and an update of the well-to-wheels analysis. In order to provide additional guidance to the program, a study is underway to identify specific issues that could threaten achievement of a commercially sustainable system.

The Phase 3 NRC report on the FreedomCAR and Fuel Partnership (NRC, 2010) recommended that DOE broaden the role of FPITT to include an investigation of hydrogen, biofuels utilization in advanced combustion engines, and electricity generation requirements for PHEVs and BEVs. Subsequently, the Partnership elected to maintain FPITT's focus on hydrogen. Although the current committee recognizes that DOE maintains communications and coordination among the various fuels-related programs within DOE, the mechanism for balancing program priorities and identifying gaps among different fuel options to

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[5] See the NREL publication *Hydrogen Pathways, Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery and Distribution Scenarios*, available at http://nrel.gov/docs/fy10osti/46612.pdf.

increase energy security and reduce GHG emissions is not apparent, as discussed above in the section "Strategic Input Needed from Executive Steering Group."

Recommendation 4-2. The fuels pathways integration effort provides strategically important input across different hydrogen pathways and different technical teams to guide U.S. DRIVE Partnership decision making. In this time of budget restraints, the program of the fuel pathway integration technical team should be adequately supported in order to continue providing this important strategic input.

HYDROGEN PRODUCTION

The hydrogen production program includes hydrogen generation from a wide range of primary energy sources, including natural gas, coal, biomass, solar, and wind. Thermal, electrolytic, photolytic, biological, and photoelectrochemical (PEC) processes are being investigated to convert these primary energy sources to hydrogen for use in fuel-cell-powered vehicles. The hydrogen production technical team (HPTT) helps guide this program toward commercially viable technologies through nonproprietary dialogue. This team includes representatives from DOE, four energy companies, and the Pacific Northwest National Laboratory (PNNL). In addition, SunCatalytix has recently been added as an associate member.

As noted in Chapter 1, a number of important programs related to the U.S. DRIVE Partnership are carried out in other parts of DOE. Work on biomass and algae production as well as work on using solar heat and wind to produce hydrogen are not part of the Partnership. The Office of Fossil Energy supports the development of technologies to produce hydrogen from coal and related carbon-sequestration technologies, and the Office of Basic Energy Sciences supports fundamental work on new materials for hydrogen storage, catalysts, and biological or molecular processes for hydrogen production, as well as work potentially affecting other areas of U.S. DRIVE.[6] The Partnership has coordination links to each of these programs. Past programs of the Office of Nuclear Energy have included an investigation of high-temperature nuclear reactors for hydrogen production, but no funds are included for this approach currently.[7]

The hydrogen production program includes short-term and long-term approaches. In the short term, when a hydrogen pipeline system is not in place, hydrogen would be supplied from centralized plants using on-road trailers similar to (but larger than) those in commercial use today, or by small-scale generation at fueling stations using natural gas reforming or electrolysis of water. As the fleet of fuel-cell-powered cars and hydrogen demand increase, centralized

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[6] BES also manages the Energy Innovation Hub called the Joint Center for Artificial Photosynthesis, which is allocated $122 million over 5 years to make hydrogen from sunlight and water.

[7] C. Sink, Department of Energy, "High Temperature Nuclear Reactors for Hydrogen Production," presentation to the committee, June 4, 2012, Washington, D.C.

hydrogen generation plants with pipeline distribution would become increasingly attractive and would be expected to satisfy an increasing fraction of the total need with time.

The program includes pathways with which considerable commercial experience exists, as well as longer-term pathways, and is reviewed below.

Pathways with Commercial Experience

As already noted, the consumption of hydrogen in the United States is highest among industrial gases, and so there is extensive commercial experience in its production. DOE programs in coal gasification, biomass gasification, low-temperature electrolysis, and steam reforming of bio-derived liquid fuels benefit from this experience while seeking to achieve significant improvements in cost and performance.

A section on natural gas reforming, the commercial process most used today in centralized plants, is not included among the sections that follow for several reasons. The Partnership, through DOE studies, has already shown the feasibility of building small reformers for distributed generation at fueling sites and meeting the cost target, and opportunities to improve large-scale reforming are considered marginal. DOE now projects that reformers at fueling stations could produce hydrogen for \$4 per gallon gasoline equivalent (gge) or less and thus reach the target range of \$2 to \$4/gge.[8] Details regarding investment and operating costs are available online.[9] The committee agrees with DOE that at this point other parts of the program are more appropriate for U.S. DRIVE than continuing cost-reduction efforts on this approach.

Hydrogen Production from Coal and Biomass

The production of hydrogen from coal and/or biomass will likely utilize a relatively mature technology, most appropriate for the later stages of a hydrogen transition (NRC, 2008). Reasonable estimates of the timing of these later-stage requirements suggest that hydrogen production from new large-scale coal and/or biomass facilities will not be needed before 2020. Prior to that time, central production of hydrogen appears manageable from natural gas feedstocks, which currently may offer environmental and cost advantages over coal and biomass.

Status of the Department of Energy Coal and Biomass Programs

Commercial large-scale gasification plants using coal, petroleum coke, or heavy oils have been in place for many years, and a large body of experience has

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[8] T. Rufael, Chevron, and S. Dillich, Department of Energy, “Hydrogen Production Technical Team (HPTT),” presentation to the committee, January 26, 2012, Washington, D.C.

[9] See http://www.hydrogen.energy.gov/h2a_production.html.

accumulated concerning their cost and operation. Using biomass as a feedstock adds different physical and chemical properties to the fuel mix (see below), but does not fundamentally alter the relevance of this deep base of commercial gasifier experience.

The DOE program plan for coal speaks of "transitioning from hydrogen production for transportation applications to electric power applications," but the technology remains relevant for central station hydrogen, either exclusively for transportation or (more likely) for the coproduction of electricity and vehicular hydrogen, and various approaches to purification of product hydrogen are being investigated. The goals of the program are "to support the goals of FE's Office of Clean Coal in development and demonstration of advanced, near-zero emission coal-based power plants" (DOE, 2010a, p. iii). The thermochemical conversion of biomass to a syngas is supported by NREL.[10]

Three aspects of the programs involving coal and biomass to hydrogen reach beyond the commercial experience base with gasifiers:

- The capture and sequestration of the carbon dioxide (CO_2) produced in the process;
- The integrating of operations downstream of the gasifier, especially the production of electricity and fuels; and
- A significant lowering of the capital cost.

Whatever budget resources are devoted to research and development (R&D) in high-priority process components, these resources are likely to be quite inadequate for demonstrating a near-scale facility and working out the systems integration issues that inevitably arise.

Environmental Issues

Concern for global climate change is much greater with coal than with biomass. The DOE hydrogen-from-coal activity has held the proving of the feasibility of a near-zero emissions plant as a key program goal. Achieving wide-scale deployment, however, will depend on the pace and accomplishment of the DOE's carbon sequestration programs. Until the commercial availability and societal acceptance of full-scale carbon sequestration can be assured, there seems to be little point in demonstrating a hydrogen-from-coal plant. Unless the carbon emissions can be addressed in a satisfactory way, commercial production seems unlikely to go forward regardless of the other merits of the technology. In contrast, hydrogen from biomass could be partially carbon neutral but might raise other environmental concerns around land use.

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[10] See http://www.nrel.gov/biomass/proj_thermochemical_conversion.html.

Feedstock Issues

In contrast with coal, a biomass production plant faces cost issues inherent in its feedstock. Whereas the coal feedstock is relatively cheap and abundant, the biomass feedstock raises a number of cost-related issues. First, the availability of feedstock limits the scale and location of biomass production plants. As a result, these are likely to face larger capital cost and transportation challenges. Second, the seasonal variability of biomass, both in its quantity and in its physical and chemical properties, will pose operating challenges. And third, storage, handling, and preparation of the feedstock to the specifications of individual gasifiers will add to cost. In addition, the type of biomass employed—for example, cellulosics, lignins, and so on—and variability of that feed will affect the gasification process.

Conclusions Regarding Hydrogen Production from Coal and Biomass

The chief issues for both the coal and biomass feedstocks center around capital cost, an observation made in the NRC (2008, p. 37) report. As that report noted: "Although coal gasification is a commercially available technology, to reach the future cost estimates . . . further development is needed. Standardization of plant design, gas cooler designs, process integration, oxygen plant optimization, and acid gas removal technology show potential for lowering costs. Other areas that can have an impact on future costs include new gasification reactor designs (entrained bed gasification) and improved gas separation (warm or hot gas separation) and purification technologies. These technologies need further R&D before they are commercially ready."

Yet as long as natural gas remains as abundant, secure, and inexpensive as the current Energy Information Administration (EIA, 2012) projections indicate, a hydrogen transition appears supportable at least through 2020, and quite possibly beyond. Thus the hydrogen from coal and biomass efforts should remain focused on fundamental R&D, as noted above, and on scientific fields that might offer value in programs beyond hydrogen production, such as separation membranes, for example.

Recommendation 4-3. While a hydrogen-from-coal demonstration plant could address many of the downstream integration issues and thus provide more certainty around the probable capital costs, the committee recommends that any hydrogen-from-coal demonstration should be paced (1) to match the pace and progress of commercial-scale carbon sequestration and (2) to support a mature hydrogen fuel cell vehicle fleet in the event that natural gas becomes too costly or unavailable.

Regarding item 1 in Recommendation 4-3, the committee notes that progress in commercial-scale carbon sequestration remains highly uncertain. As a recent interagency report notes, "The lack of comprehensive climate change legislation is the key barrier to CCS [carbon capture and sequestration] deployment. Without a carbon price and appropriate financial incentives for new technologies, there is no stable framework for investment in low-carbon technologies such as CCS" (DOE, 2010b, p. 10). Until this fundamental policy issue is resolved and the CCS process is demonstrated to be effective and safe for long-term storage of CO_2, private investment in unsubsidized coal-to-hydrogen plants is likely to pose commercially unacceptable risks. Regarding item 2 in Recommendation 4-3, the opening stages of a transition to the HFCV appear supportable from natural gas feedstocks. For these reasons, continuing DOE's basic R&D while deferring any demonstration of hydrogen from coal until conditions warrant seems appropriate.

Low-Temperature Water Electrolysis

The low-temperature (below 100°C) electrolysis of water is a mature hydrogen generation technology that has been used in military and industrial applications for decades. Electrolysis is an attractive solution to on-site hydrogen demand, as electrolyzers can be sited in nearly any location and can be scaled to meet volume requirements. Furthermore, the two primary electrolyzer technologies, alkaline and proton exchange membrane, can generate hydrogen without carbon emissions if powered by a renewable energy source. Although the membrane process has received the most attention in recent years, the alkaline process is the most commonly utilized, especially in large-scale industrial applications. The attractiveness and potential benefit to the fuel cell community stem from the fact that high-purity hydrogen can be generated by a relatively simple process and sited in geographical locations where other hydrogen generation processes are not feasible. Additionally, with respect to vehicle refueling, the hydrogen can be generated at high pressures, thereby eliminating the need for mechanical compressors.

Due to the nature of the electrolysis process, the technology can be used in small or large operations, making it ideal for lower-volume opportunities, including distributed, point-of-use applications such as home refueling or large-scale centralized production. Additional attractive aspects of the current electrolysis processes are durability and lifetime, as decades of operation without significant performance degradation and losses have been the norm. The electrochemical efficiency of the electrolysis process itself is approximately 80 percent (higher heating value [HHV]); when the entire system (balance of plant) is taken into account, efficiencies in the high 50s or low 60s can be achieved (excluding the power source efficiency contribution) (NREL, 2004, 2009, 2012).

Primary Disadvantage: Cost. The primary disadvantage of water electrolysis is cost, both operating expenditure (OPEX) and capital expenditure (CAPEX). The energy requirement to split the water alone is significant (more than 50 kWh/kg), as are the capital costs related to the hardware—for example, stack components and the balance of plant. It should be noted that the balance between OPEX

TABLE 4-1 Draft Targets (2015, 2020, and Ultimate) and Current Status for Hydrogen Production Using Water Electrolysis (\$/kg H_2) (Excluding Cost of Hydrogen Delivery)

Method of Generation	Current Status	2015 Target	2020 Target	Ultimate Target
Distributed	\$4.00	\$3.70	\$2.20	\$1.00-\$2.00
Central	\$4.60	\$3.10	\$2.00	\$1.00-\$2.00

NOTE: During the committee's review, U.S. DRIVE representatives noted that the targets were under review for possible revision.
SOURCE: T. Rufael, Chevron, and S. Dillich, Department of Energy, "Hydrogen Production Technical Team (HPTT)," presentation to the committee, January 26, 2012, Washington, D.C.

and CAPEX is volume-dependent, as the smaller, lower-volume units are more capital-intensive, whereas the higher-volume units are more expensive to operate on a per kilogram of hydrogen basis. The current cost of producing hydrogen by the electrolysis process, central or distributed, is still significantly above the 2020 DOE targets of \$2.20/kg H_2 and \$2.00/kg H_2, respectively (see Table 4-1).[11] Although the annual budget for hydrogen production (all technologies) has been reduced over the past 3 years, from approximately \$28 million (FY 2008) to approximately \$11 million (FY 2011), the DOE appropriately continues to support the longer-term initiatives that ultimately could reduce electrolysis stack hardware costs, advanced membranes, and new catalysts.

Generating electrolytic hydrogen without emissions is possible with a number of renewable energy sources—wind, solar, and hydroelectric power, to name a few. In order to better understand this approach, in recent years DOE has funded studies through NREL to assess hydrogen generation costs by means of a renewable wind energy electrolysis process (NREL, 2008a, 2008b). Conclusions from the cost-benefit configuration studies indicate that plant size (volume), utilization, and energy availability (wind source and strength) are critical factors in achieving the cost targets. The studies further show that under a number of conditions and assumptions, \$3.00/kg H_2 (gge) production costs could be achieved. The significant disadvantage of the wind electrolyzer approach is that the system must still be grid-connected for off-wind periods. The reports further highlight the impact on cost of the *system* architecture and engineering, including controls and software, water conditioning, the power electronics, and gas cleanup and drying. These assessments provide valuable insight into how hydrogen production rates and system utilization can impact cost, thereby providing direction to DOE about where funding would be best allocated.

As noted above, a number of sources indicate that electrolysis may be a viable hydrogen production pathway if costs and greenhouse gas emissions from electric

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[11] Note that the energy value of a kilogram of H_2 is approximately the same as a gallon of gasoline equivalent (gge); thus, these targets can also be expressed as \$/gge.

power generation can be reduced. The DOE's response has been appropriate, proactively supporting long-term projects focused on next-generation technical solutions. As reported at the DOE Annual Merit Review meetings (2010, 2011, 2012), progress has been made in recent years. According to one effort, focusing on hardware elements has yielded significant cost-reduction advancements (see Figure 4-1). New cell materials, architecture, and ultimately advanced manufacturing methods will impact the capital on a kilogram-of-generated-hydrogen basis. Performance characteristics of the electrochemical process are predominately tied to membranes, electrodes, and catalysts, topics also currently supported. The membrane R&D is appropriately focusing on conductivity improvements and alternative polymers, while the primary electrode development effort is evaluating thin-film nanocatalyst materials (3M), similar to those developed for the fuel cell industry.

Regardless of the source of hydrogen, it is clear that for there to be the possibility of widespread HFCVs, there must be the availability of hydrogen for refueling. One possibility being pursued is that of using on-site electrolysis of water to locally produce hydrogen using wind power, which would both avoid GHGs produced (by the power plants) and reduce energy lost in the process of energy conversion at the power plant and transmission and distribution.

Appropriateness of DOE Funding. The operating and capital costs of electrolyzers as presented in Table 4-1 and Figure 4-1 must be reduced if they are to become a viable option and the hydrogen cost targets of \$2 to \$4/kg H_2 are to be met. Research and development activities on the stack as well as on the balance of plant (predominately the power electronics) need to continue, as does integration with the energy sources. As the cost issue is related to the technology, the currently funded research topics previously discussed in the DOE portfolio of long-term projects continue to be needed. It seems appropriate that the DOE

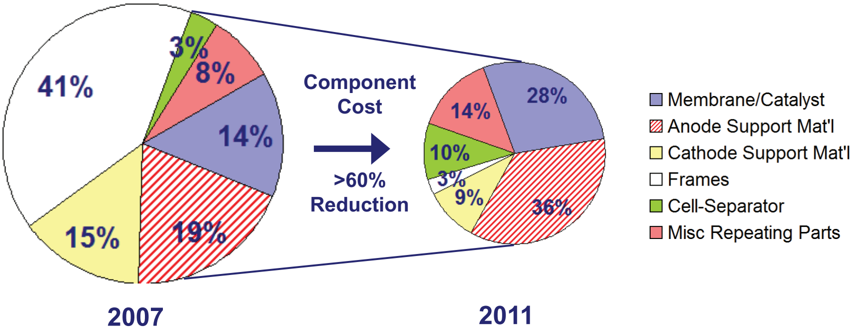

FIGURE 4-1 Cost-reduction progress between 2007 and 2011 in membrane electrolysis stacks. SOURCE: Hamdan (2011).

programs focus on evaluation of the entire system, including the technical and cost benefits of advancements in power electronics as well as the impact of high-pressure electrolytic hydrogen generation for refueling operations.

Even though electrolysis is widely practiced commercially, its components and power electronics for refueling applications can still be improved, resulting in reductions in capital and operating cost.

Recommendation 4-4. Support should continue at the fundamental component level (e.g., catalysts, anode supports) for all types of electrolyzers as well as for associated power electronics.

High-pressure electrolytic hydrogen generation provides an avenue to significant cost savings in the dispensing of hydrogen in distributed applications at fueling stations by eliminating mechanical compression and purification subsystems.

Recommendation 4-5. Technical development and systems analysis on high-pressure electrolytic hydrogen production should be supported to determine the costs, scalability, benefits, and developmental steps required to make it viable compared with conventional compression. With the goal of eliminating mechanical compression, additional work should be done on high-pressure electrolysis that can produce pressures of 84 MPa to 98 MPa (12,000 to 14,000 psi) and have sufficient capacity to do a fast tank fill (3 minutes).

Recommendation 4-6. The U.S. DRIVE Partnership should continue to support the development, testing, and analysis of (distributed) renewable electricity production methods in combination with the electrolysis of water.

Distributed Steam Reforming of Bio-Derived Liquid Fuel

Just as natural gas can be steam reformed in small refueling stations to produce hydrogen on-site, other liquid fuels can be also. If the liquid fuel is produced in a low-GHG-emissions method, which is possible from biomass, then this affords the opportunity of making low-GHG-emissions hydrogen on a distributed basis. A number of bio-derived fuels have been investigated, ranging from ethanol to heavy oils produced from biomass pyrolysis. From a technological perspective, it is straightforward to reform ethanol, but because of ethanol's high cost the resulting hydrogen cost is not competitive with other methods of making hydrogen. Depending on future regulated costs for CO_2 emissions, this pathway could become more competitive.

The DOE has investigated the reforming of other bio-derived liquids that might provide a more competitive hydrogen cost. It has supported early-phase research into both gas-phase and liquid-phase reforming of a variety of bio-derived liquids. The major technical barriers include catalyst activity and selectivity issues along with catalyst coking issues. As a result of these efforts, some progress in yield improvements has been observed in laboratories, and a better understanding of the economics of the overall pathway is estimated. Through this work it appears that a very low bio-derived liquid cost is required to meet future hydrogen cost targets. Costs of less than $1/gal may be required for the bio-derived liquid. This may be the largest hurdle for this pathway.

The committee considers the reforming of bio-derived liquids to be an appropriate area for DOE funding, which for the past several years has been approximately $1 million per year. The funded projects are scheduled to be completed in FY 2013, and no additional funded projects are anticipated in FY 2013.

Longer-Term Pathways

The DOE is also pursuing several approaches to hydrogen production that are in their early stage of research and development, and much improvement in cost, performance, and efficiencies is needed before they are ready for commercialization. If successful, these approaches have the potential to reduce the energy requirement for hydrogen production, dependence on fossil fuels, and carbon emissions. These approaches include high-temperature water splitting, PEC processes, solar thermal conversion, and biological generation.

Emerging Hydrogen Production Technologies

Splitting water into its elements by a solar mirror system (solar thermal [ST] process) or by a PEC process involves techniques that capture solar energy to convert water directly into hydrogen. Both processes have been under investigation for decades, resulting in steady but slow progress. Both approaches are still far from being commercially viable and are faced with cost and technical challenges, yet they represent the potential to contribute to the generation of hydrogen by means of a renewable energy source.

Progress in the PEC approach has accelerated in the past decade, especially in new photoactive electrode materials that can utilize visible light and exhibit enhanced stability in an aqueous medium, such as Ti oxynitride (Maeda and Domen, 2010). Other materials that show promise include MoS_2, sub-stoichiometric oxides, and selected non-oxides—for example, SiC, selected nitrides, and III-V as well as I-III-VI tandem semiconductors (GaInP2/GaAs). Nonetheless, challenges remain, including (1) low solar-to-electrochemical hydrogen efficiencies and (2) for many materials, the chemical stability, although efficiencies as high as 12 percent have been reported (NREL, 2010). Whether the PEC process has significant inherent advantages compared with combined photovoltaic and electrolysis processes remains to be determined. However, the Joint Center for Artificial Photosynthesis (JCAP) at the California Institute of Technology and the Lawrence Berkeley National Laboratory (Berkeley Lab) has been established as an Energy Innovation Hub by DOE; JCAP could identify promising approaches for utilizing solar energy in electrochemical hydrogen production.

The second technique, the combination of high-temperature water-based redox chemistry with a thermal (solar) source—that is, the ST process—is an approach that is gaining interest because of (projected) economics. This technique has geographical limitations, but its scalability and overall simplicity make it attractive. High-temperature decomposition of water by coupling with a metal oxide redox cycle has been studied and supported by DOE for some time. The challenge has been finding materials with rapid oxidation/reduction kinetics, low thermal mass, and long-term stability and devising a continuous process that does not require large temperature swings. The DOE has been funding national laboratories, academia, and industrial partners in early-stage research for the past few years, focusing on various redox cycles and reaction and process engineering. Process modeling is progressing and will soon be validated in a 10 kW_{th} thermal reactor currently in the design phase. The recent H2A study by TIAX on the costs associated with a number of thermochemical processes indicates that the ferrite process is the only one projected to meet the DOE cost targets of \$3/gge (TIAX, 2011).

Electrolysis at an elevated temperature (a few hundred degrees) and the coupling of thermal decomposition cycles with electrolysis (e.g., electrolysis to generate hydrogen and a sulfur redox cycle for oxygen evolution) are also technically possible. They are also faced with material stability challenges and/or process complexity.

DOE support of these programs is appropriate, as they are still at the proof-of-concept phase. However, in view of the tight funding situation, continued support should be weighed against other programmatic needs, considering the viability of the approaches to meet the program goals in a reasonable time frame and the dependence on breakthrough innovation and inventions. A modest level of funding should lead to evaluation of the potential impact and likelihood of meeting program goals with these emerging technologies. Interactions with JCAP are encouraged so as to disseminate fundamental catalysis knowledge on hydrogen generation processes currently under study.

Biological Generation of Hydrogen

Biological generation (Lee et al., 2010; Hallenbeck et al., 2012) offers a possible long-range approach for effectively providing the energy input to produce hydrogen at low cost. Given the early stage of research for this method, DOE is appropriately, in the committee's view, exploring a number of biological pathways to identify those that appear most promising.[12] The results of these early

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[12] The committee is very much appreciative of and indebted to Professor Laurens Mets, University of Chicago, for his expert information and comments.

investigations may eventually lead to a development program. These pathways are described below.

One approach to the production of hydrogen by means of a biological process is through photosynthesis, using both of the photosystem components found in green plants. In this process, two photons absorbed by photosystem II split the water molecule, and two more, absorbed by photosystem I, transfer two electrons to transform the protons from the split water molecule into a hydrogen molecule. The process can be carried out by green algae, by cyanobacteria, or purple bacteria, which use small organic molecules rather than water as their source of hydrogen. All three use solar energy to provide the driving force for the process. Enzymes, hydrogenases in the first two cases and nitrogenase in the third, “do the work.” The hydrogenase work, being done at NREL, is currently supported by DOE at $350,000 for FY 2012. In principle, it might be possible to carry out the entire hydrogen production with only photosystem II, which would virtually double the production rate of hydrogen. However, no suitable catalyst has been found that can achieve that single-step generation, and so processes potentially available now all require both photosystems and hence a low production rate. The process is carried out in water, which need not be pure; in fact, some “contaminants” can serve as nutrients for the bacteria or algae.

An enduring problem for bioproduction of hydrogen photolytically is the sensitivity of both photosystems to molecular oxygen; O_2 inactivates the processes. If the oxygen generated by water splitting fails to escape from the reaction center, it inactivates the process. Some efforts have been carried out to try to reduce the oxygen sensitivity of the hydrogenase enzymes, the enzymes that generate the hydrogen. Replacing one of the iron atoms in the enzyme by a nickel atom does increase the oxygen tolerance, but at the cost of reducing the rate of hydrogen generation. Among the approaches being explored, perhaps the most promising currently uses ferrodoxin as the electron donor to the protons and an enzyme tolerant of oxygen for the splitting. This remains an unsolved problem. Platinum nanoparticle catalysts have also been used to enhance the activity of photosystem I, instead of an enzyme. Typical overall efficiencies today may reach 1 percent, whereas an efficiency of at least 10 percent is considered economically necessary. Hence this goal currently seems rather far away. This work, going on at the Craig Venter Institute, has $150,000 in support from DOE for FY 2012.

Fermentation methods, particularly photofermentation, for biological production of hydrogen have been studied primarily at the National Renewable Energy Laboratory. The support level from DOE for FY 2012 is $350,000. The results appear thus far to be very inefficient and expensive. The yields are very low, but nevertheless higher, typically, than the yields from biophotolysis. One inherent disadvantage of this method is simply that it involves conversion of a high-energy-density material into hydrogen, a material with lower energy density. In effect, it is downgrading a high-energy material. It might be better to find a way to operate vehicles with glucose as fuel than to ferment the glucose to make hydrogen intended to be a vehicle fuel. If fermentation of organic waste were to be developed into an economic, modestly efficient process, then perhaps hydrogen production by fermentation might become an attractive process. A very recent approach based on this method uses what are normally waste materials from the sugar industry—blackstrap molasses and beet molasses—as inputs for a one-stage process. This might become a viable photofermentation method for hydrogen generation (Keskin and Hallenbeck, 2012). Photofermentation has been under study at NREL, where *Clostridium* is being used to produce hydrogen from cellulosic materials.

Dark fermentation, an anaerobic process not involving the input of energy from light, is another related approach, one that typically uses organic waste materials as the source, with carbohydrates such as cellulose as the primary hydrogen source. The DOE is currently investigating this approach. Because the process is anaerobic, deactivation of enzymes by oxygen is not a problem with it. However, it produces a number of undesirable waste products and only a limited amount of hydrogen, and it also converts high-energy materials into what hydrogen it does generate. The yields are still low; CO_2 is a major, unavoidable by-product; and the substrates are expensive at this time; thus, it does not currently appear to be one of the most attractive among the biological approaches to hydrogen generation.

Algae can produce hydrogen, and DOE is currently supporting two projects to investigate this direction. One is at the University of California, Berkeley, at a level of $150,000 for FY 2012; the other is at NREL, at $600,000 for the same period. Algae may prove effective as biogenerators of hydrogen, but one consideration may make that approach less attractive than microbial generation—namely, the greater difficulty of manipulating the genetics of algae compared with those of bacteria. Nevertheless this does seem to be a direction worth pursuing at the R&D level.[13]

Microbial electrolysis is an approach with some long-term potential. By attaching bacteria to an anode (anode-respiring bacteria, or ARB), the microbes can oxidize organic materials and transfer the electrons so released to that anode, thereby generating an electric current. This then electrolyzes water at the cathode to produce hydrogen. A small voltage must be added to that developed at the anode in order to decompose water molecules, but this is only an addition of about 0.13 volt, far less than the 0.82 volt required for the electrolysis. The method is capable of giving high yields, and also of using the products of dark fermentation as inputs. To make the method efficient, the applied (added) voltage must be low and the losses, too, must be kept low. Yet it must be high enough to overcome the inherent losses of the system. At the same time, the current should be maximized because that is what determines the rate of production of hydrogen. Various techniques are under investigation now to try to make microbial electrolysis a viable source of hydrogen, but the outcome is still extremely uncertain. The DOE is currently supporting this effort for FY 2012.

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[13] Another NRC committee has been studying sustainability issues of algal biofuel production. Its report was issued in the fall of 2012 (NRC, 2012).

In all of the approaches, researchers are exploring the possibilities that genetic modification of the appropriate microorganisms could perhaps overcome current limitations on the performance of bacterial and algal methods of hydrogen production.

One other approach under study at NREL is the production of hydrogen by pyrolysis or gasification of biological wastes. This method uses biological materials but does not involve any biological processes. The approach generates a mixture of products, one of which is hydrogen, which of course would have to be separated from the other products.

DOE funding for biological generation of hydrogen, which includes all of the above methods and excludes biomass gasification, was $1.67 million in FY 2011; the planned level for FY 2012 is $1.6 million.

HYDROGEN DELIVERY AND DISPENSING

Hydrogen delivery, storage, and dispensing account for a substantial part of both the delivered cost of hydrogen for HFCVs and the efficiency of the overall system. In a fully developed hydrogen economy, the postproduction part of the supply system for high-pressure hydrogen will probably cost as much as production and consume as much energy (NRC/NAE, 2004). Improvements continue to be made in both production and postproduction, but the relative importance of the two areas has not changed significantly. Distribution costs are of even greater concern during the transition period when the demand is low, particularly when hydrogen from centralized plants is available. In that case, distribution could easily cost more than production does.

Dispensing systems for gaseous hydrogen must be designed to prevent excessive temperature increases in the vehicle tank during pressuring and filling, particularly for the 700-bar (approximately 70 MPa, or 10,000 psi) operation. As a result, communication between the vehicle and the refueling dispenser is required so that pressure and temperature can be monitored and controlled.

This program is advised by the hydrogen delivery technical team, with membership from DOE, five energy companies, the U.S. Department of Transportation, the Argonne National Laboratory, and the Oak Ridge National Laboratory. In addition, Praxair has recently been added as an associate member. The effort is focused on three delivery pathways: transmission and distribution of gaseous hydrogen from centralized plants by tube trailer and by pipeline, and of liquefied hydrogen by tanker. The overall target is to reduce the cost of delivering and dispensing hydrogen to $1 to $2/gge. The committee believes that this is an aggressive but appropriate target, assuming that the required funding continues to be available.

In the past 2 years, there have been significant achievements in the area of hydrogen delivery and dispensing. The projected cost of transport by tube trailers has been reduced by 40 to 50 percent using a 35-MPa (350-bar), carbon-fiber-wrapped tube trailer with a carrying capacity of 800 kg of hydrogen or a glass-fiber vessel with a capacity of 1,100 kg. In addition, there have been reductions in the installed cost of pipelines, pipeline compressors, and forecourt hydrogen storage. Further, projected hydrogen liquefaction efficiency and forecourt compressor reliability have been increased.

In 2011, researchers at FuelCell Energy, Inc., demonstrated the feasibility of employing hydrogen electrolysis to compress the gas to 7,000 psi.[14] The company is currently modifying the design to achieve higher pressures. This device shows promise of replacing the single most expensive component of a hydrogen refueling station, the high-pressure compressor, while also improving efficiency. This approach should be evaluated for reaching the design pressure and should be compared with conventional compression by U.S. DRIVE, as recommended in the discussion of low-temperature electrolysis.

The Phase 3 NRC (2010) report recommended that this program be based on the activities needed to meet the 2017 cost target, and if that was not feasible, it recommended that the focus be on areas most directly impacting the 2015 decision regarding commercialization. Further, the Phase 3 report recommended that the cost target should be consistent with the program actually carried out. The DOE has been responsive by updating the technical targets and revising its cost target.

The planned budget for FY 2012 is $5.7 million, compared with an appropriation of $6 million in FY 2011. Future efforts will be focused on reducing the cost of fueling station hydrogen compression and storage as well as the delivery costs for early market applications. The committee believes that this is an appropriate use of federal funds and that a stable funding level must be maintained in order to have a reasonable chance of success in meeting the cost targets.

BIOFUELS AND U.S. DRIVE

The emphasis for the U.S. DRIVE Partnership is on developing technologies for HFCVs and hydrogen production, BEVs and PHEVs that can connect to the electric grid, and improved internal combustion engine (ICE) systems. Biofuels used in these improved ICEs can be an important option for reducing the use of petroleum-derived fuels while also reducing the GHGs of transportation.

Within DOE, the Biomass Program has the responsibility for managing the development of biomass growth, harvesting, storage, and delivery R&D programs. The Biomass Program also manages the R&D programs for biomass conversion to biofuels and the distribution of biofuels to the market. Historically the Biomass Program interfaced with the U.S. DRIVE Partnership or its predecessors on issues

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[14] J. Simnick, BP, and S. Weil, Department of Energy, "Hydrogen Delivery Technical Team (DTT)," presentation to the committee, January 27, 2012, Washington, D.C. Since this presentation, pressure at more than 12,000 psi with a single stage of electrochemical compression has been demonstrated (Lipp, 2012).

of fuel distribution and on characterization and combustion of different biofuels and mixes of biofuels with conventional petroleum-derived fuels. The committee is reviewing only U.S. DRIVE activities and not the Biomass Program activities, and so its comments here are directed only toward U.S. DRIVE.

This interface between the U.S. DRIVE Partnership, which has a focus on the combustion technology, and the Biomass Program can be useful in helping the management of both programs better assess the state of development of the different vehicle/biofuel pathway approaches and understand how and when commercial deployment of large quantities of biofuels could occur. The three primary alternate vehicle/fuel pathways (HFCVs, BEVs and PHEVs that can plug into the electric grid, and biofuels for ICEs) are at different states of development and deployment, and progress in one affects the R&D emphasis and targets of the others.

Biofuels Development Strategy

The Biomass Program R&D emphasis has changed over the past several years, and this has an effect on the U.S. DRIVE tasks. Prior to 2010, R&D on making cellulosic ethanol was a strong focal point for the Biomass Program. This emphasis then gave reason for U.S. DRIVE to investigate ICE performance of various combinations of ethanol and gasoline. There was also reason to investigate distribution problems with ethanol in order to reduce costs. Starting in 2010 the Biomass Program reduced its ethanol programs and increased its programs to make biofuels, sometimes called drop-in fuels, that are thought to be indistinguishable from petroleum products. These can be produced as gasoline, jet fuel, or diesel-type finished products. Biomass sources include woody biomass and energy crops. Drop-in fuels require neither special ICE technology nor special infrastructure distribution systems.

These drop-in fuels can be made from cellulosic sources using various biochemical and thermochemical approaches. Among them are the following:

- Gasification followed by Fischer Tropsch plus finishing processing,
- Gasification followed by methanol-to-gasoline processing, and
- Pyrolysis followed by hydrotreating and hydrocracking processing.

As there are several different methods for making drop-in fuels, their development is at different states. Laboratory and bench-scale work is still required to develop catalysts and less costly process flow schemes for some options, while others are in the large-pilot-plant phase. It is not yet known if any of the processes will result in competitively priced fuels; however, studies indicate such potential if research is successful. Target dates for R&D appear similar to those for hydrogen, setting competitive cost targets in the 2017 time frame. The Biomass Program is also investigating longer-term sources, such as algae, that are in much earlier stages of development.

U.S. DRIVE Role

In the United States, about 13 billion gallons of ethanol made from corn are blended into the gasoline mix of about 135 billion gallons of gasoline, almost 10 percent by volume and 6.6 percent by energy content. Little more ethanol from corn is expected in the mix, as current legislation, the Energy Independence and Security Act (EISA) of 2007 (Public Law No. 110-140), limits the corn-based ethanol to approximately today's volume. This act sets targets for cellulosic ethanol and other cellulosic biofuels that increase yearly until the total biofuel volume reaches 36 billion gallons of ethanol equivalent by 2022. The target volumes have not been met for the past several years. A recent NRC (2011) report on the Renewable Fuel Standard (RFS) concluded that, absent major technological innovation or policy changes, the EISA of 2007-mandated consumption of 16 billion gallons of ethanol-equivalent cellulosic biofuels is unlikely to be met in 2022.

The biofuel role for the U.S. DRIVE Partnership in this scenario is different from the Partnership role in the past, when ethanol appeared to be a larger-volume possibility and more considerations were needed for higher ethanol fuel blends and problems with distributing ethanol. There is a continuing need for future biofuels, which have been and will continue to change in type and quality, to be compatible with the evolving ICE developments. A U.S. DRIVE focus on ICE development that can handle drop-in fuels and other biofuels is warranted.

NATURAL GAS OPPORTUNITIES FOR U.S. DRIVE

The significantly increased estimates of reserves of domestic natural gas determined in the past several years, brought about by new production technologies, are having profound effects on the domestic energy markets.[15] Production levels have increased over the past several years while market prices have decreased to levels not seen in over a decade. The market is already seeing increased use of natural gas to make electricity, with a corresponding reduced use of coal. The chemical industry is benefiting from the lower feedstock prices and increased availability of natural gas and the associated light hydrocarbon liquids. The economic incentive for homeowners to switch from heating their homes with heating oil derived from petroleum to natural gas is larger than ever.

In the transportation markets, natural gas has only been considered a marginal basic resource for alternate transportation fuels in the past because of limited domestic availability and the perceived need to increase imports in the form of liquids (e.g., liquefied natural gas [LNG]) just to meet demand in the traditional power, industrial, and residential markets. Imports of LNG are considered similar

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[15] The 2011 Potential Gas Committee (April 27, 2011, Golden, Colorado, Colorado School of Mines) estimates potential natural gas resources of 1,898 trillion cubic feet (Tcf) and proved resources of 272 Tcf. At the 2010 annual consumption of 24.1 Tcf, this represents 90 years of supply, which is up from 86 years of supply 2 years ago.

in nature to imports of petroleum crude oil, with similar negative economic and political considerations. With the additional domestic reserves and supply now estimated by the EIA in its *Annual Energy Outlook* (EIA, 2012), and the resultant lower prices compared to those for crude oil, natural gas is now projected to be an economic source to provide transportation fuels. This change should shift the priorities and direction of all alternate vehicle and fuel research, development, and demonstration (RD&D) programs.

The additional reserves and supply of natural gas affect alternate vehicle pathways in different ways and to different extents. These now must be taken into consideration when comparing different vehicle and fuel pathways. Some of the pathways affected are as follows:

1. It is possible to use gasoline and diesel fuel derived from natural gas (e.g., gas to liquids) at costs competitive with those for fuel from crude oil.
2. Other liquid fuels derived from natural gas, such as methanol, are possible at larger volumes and lower costs.
3. Replacing coal with natural gas in power generation lowers the GHG emissions of the electricity used to power BEVs and PHEVS and to produce hydrogen using electrolysis.
4. Transitioning to hydrogen is more straightforward, with lower projected costs and GHG emissions when more natural gas is the basic source for the hydrogen.
5. It is possible to use natural gas as a direct vehicle fuel, compressed natural gas (CNG), in a light-duty vehicle (LDV) at costs competitive with those for petroleum-derived fuels.

The U.S. Compressed Natural Gas Opportunity

Compressed natural gas is used as a direct fuel in more than 10 million vehicles around the world, usually in locales with an inexpensive natural gas price compared with the price of gasoline. It generally is considered a fuel of opportunity based on low costs. With the increased domestic reserves and resultant lower domestic prices, CNG is now an attractive fuel compared to gasoline in the United States. This favorable cost relationship is projected to continue for at least several decades (EIA, 2012).

CNG can replace gasoline made from crude oil in an ICE on a gallon per gallon basis (based on British thermal units [Btu]) with about 20 percent lower GHG emissions on a life-cycle basis. No new technologies are needed for the LDV or for the infrastructure to deliver CNG to the LDV. Regarding customer needs, in vehicles specifically designed for CNG, driving distance and interior space should be roughly comparable to those provided by gasoline-fueled ICE vehicles and HFCVs. Technology improvements that can lower both the vehicle cost and the infrastructure cost are possible. The committee expects that for the overall infrastructure, the initial investment cost per CNG vehicle could be lower than that for electric vehicles, HFCVs, and biofuel vehicles (NRC, 2013). With the existing very large natural gas pipeline system, a large part of the country could be supplied with CNG.

Although an attractive opportunity exists based on the current and midterm supply of natural gas, cost, and GHG emissions compared with those related to gasoline, the very long term role in the entire LDV fleet for the CNG vehicle is not clear. The lower GHG emissions compared with those from gasoline are beneficial but are not large enough to reach the 2050 goal of 80 percent reduction from 2005 levels without significant increases in ICE vehicle efficiency and/or reduction in vehicle miles traveled. Questions exist and are being investigated about the amount of GHGs (CO_2 and methane) actually released during natural gas production. In addition, there are other general public concerns with water contamination and some production methods (hydraulic fracturing or "fracking"). As a commodity, natural gas is subject to price variations based on supply and demand, and there is no assurance of its long-term cost advantage compared with petroleum-derived gasoline.

CNG Light-Duty Vehicle and Infrastructure R&D Needs

Several areas could benefit from further technology development primarily to lower costs for both the LDV and the fuel infrastructure. They include the following:

1. The CNG storage tank in the LDV is bulky, high-pressure (about 25 MPa, or 3,600 psi), and expensive. Improvements in volumetric and gravimetric densities are needed to be comparable in many characteristics to liquid fuel tanks. The high-pressure operation makes the tanks expensive and also increases the cost of refueling at the high pressure.
2. CNG refueling stations are commercially available today, but the high-pressure operation results in high costs. Home refueling could be beneficial in some markets, as many homes have natural gas. Home refueling equipment is expensive primarily because of the high-pressure operation.

Although natural gas and the CNG LDV are not part of the U.S. DRIVE effort, these R&D areas are being addressed by DOE through its Advanced Research Projects Agency-Energy (ARPA-E). The ARPA-E Methane Opportunities for Vehicular Energy (MOVE) program is a new effort to address both of the above issues. The ARPA-E has plans to fund projects at about $30 million over a 3-year period to help resolve these issues. Success in these areas is not guaranteed, but if it occurs, success in these areas combined with continued growth in natural gas reserves and production could make a compelling case for rapid growth in the CNG vehicle fleet.

Recommendation 4-7. U.S. DRIVE should include the CNG vehicle and possible improvements to its analysis efforts in order to make consistent comparisons across different pathways and to help determine whether CNG vehicles should be part of its ongoing vehicle program.

ELECTRICITY AS AN ENERGY SOURCE FOR VEHICLES

The amount of electricity required for individual plug-in vehicle[16] travel depends on vehicle size, weight, and other characteristics. The Environmental Protection Agency (EPA) estimates that the midsize Nissan Leaf uses an average of 34 kWh per 100 miles and that the Transit Connect Van uses 54 kWh per 100 miles.[17] Most forecasts of plug-in vehicle demand suggest that the national electric-supply-system grid will be able to support the number of electric vehicles likely to be on the road, at least to 2020. Some local supply problems could appear, possibly in Texas, for example, where a combination of grid isolation and weak incentives for new generation appear likely to cause shortages. And in some neighborhoods the clustering of plug-in vehicles might overload local circuits and transformers. But from a national perspective, the near-term grid capacity appears adequate.

Beyond that time, the energy capacity projected for the U.S. electric system also appears ample as long as the projected capacity additions are brought online (see Box 4-1). Nevertheless, three kinds of uncertainty—demand uncertainty, technology uncertainty, and policy uncertainty—will require leadership from DOE and the U.S. DRIVE Partnership to ensure the most rapid, environmentally benign market penetration and cost-effective penetration of plug-in vehicles.

Three Consequential Uncertainties

Even though the national grid appears adequate, the three uncertainties listed above remain. Their resolution will strongly influence the environmental and economic consequences of recharging plug-in vehicles as well as the pace of the acceptance of plug-in vehicles in the marketplace. Resolving the uncertainties in a favorable manner will require rapid learning and effective response on the part of DOE, the U.S. DRIVE Partnership, and state policy makers. Discussed in the sections below, the uncertainties can be briefly described as follows:

- *Demand uncertainty* regarding the ways that consumers will recharge these vehicles, and how (or whether) customers will use "smart-home"

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[16] "Plug-in vehicle" here is meant to include any vehicle relying on electric energy that is supplied externally, most likely from the national electric grid. In the terms most commonly used, this includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and extended-range electric vehicles (EREVs). Generically, since all of these vehicles are dependent to one extent or another on electricity from the grid, they are sometimes all referred to as electric vehicles (EVs).

[17] See, for example, http://www.fueleconomy.gov/feg/evsbs.shtml.

BOX 4-1
The Plug-in Vehicle and the U.S. Electric Supply System

The impact of the plug-in vehicle on the grid depends on the market penetration of electric vehicles (EVs, which include both plug-in electric vehicles [PHEVs] and battery electric vehicles [BEVs]). Forecasts vary widely. For example, Deloitte Consulting projects the 2020 U.S. market share for EVs to range from 2.0 to 5.6 percent of the new-vehicle market, or between 285,000 and 840,000 vehicles per year (LaMonica, 2010). Also, Edmunds.com projects annual EV sales of 250,000 by 2017, which would put it within the Deloitte range by 2020 (Shepardson, 2012).

If it is assumed conservatively that the number of PHEVs sold increases linearly to reach 1 million per year by 2020, that would imply an EV fleet of, at most, 4 million vehicles operating in that year. If each of these vehicles recharges a 10-kWh (usable depth-of-discharge) battery twice a day, every day for a year, the total kilowatt-hours consumed in 2020 would be about 29 billion. In contrast, the Energy Information Administration estimates that the national electric grid will be able to produce 4,159 billion kWh in 2020 (EIA, 2012). Thus even a highly optimistic case for plug-in vehicle penetration suggests that the electric energy demand of plug-in vehicles will prove manageable.

To be sure, a national or even state restriction on carbon emissions severe enough to shut down large numbers of coal-fired power plants could make this forecast unachievable. But absent such an occurrence and from a national perspective, the energy demands imposed by the EV fleet appear to be manageable.

technologies in ways that offset the grid impacts of plug-in vehicle charging;

- *Technology uncertainty* regarding the speed of deployment of smart-grid technologies and advanced charging systems that allow rapid charging; and
- *Policy uncertainty* regarding the nature and strength of rate incentives for consumers to recharge their vehicles and for the electric utility companies or others to invest in the necessary infrastructure.

These uncertainties cannot be addressed independent of one another, but rather must be resolved in their entirety. Leadership from DOE and the U.S. DRIVE Partnership will prove essential for their timely and effective resolution. Absent that leadership, the market penetration of all plug-in vehicles could be delayed and their environmental and economic benefits blunted.

Demand Uncertainty

The location and time at which the users of plug-in vehicles will choose to recharge their batteries remain quite uncertain for several reasons. First, regarding location, many grid analysts note the tendency of plug-in ownership to occur in neighborhood clusters (May and Johnson, 2011). According to this "cul-de-sac effect," plug-in vehicles tend to gravitate toward wealthy neighborhoods and environmentally conscious communities. The consequence can overload local circuits and transformers. Consider, for example, a Nissan Leaf recharging on a 240-volt, 15-amp circuit. This imposes a 3.3-kW load on the circuit, which is greater than the load of the average home in Berkeley, California. Similarly, a Chevy Volt recharging on a 240-volt, 30-amp circuit imposes a 6.6-kW load, about the average for homes in San Ramon, California (May and Johnson, 2011, p. 56). Since utility circuits and transformers tend to be sized to accommodate five or six homes, just a few vehicles can change the power loading of a circuit markedly. Thus, the charging issues posed by clusters of activity could challenge many early-adopter communities and utilities.

Second, regarding time, the chief concern of vehicle users is the worry about becoming stranded with a depleted battery. And so vehicle owners have an incentive to recharge their vehicles' batteries at every opportunity: while at work, in parking garages, while parked at airports, and so forth. Thus, utility planners cannot assume that all charging will be done at night when the electric grid has off-peak power.

Third, the prospect for fast charging (see the section below) could make the plug-in vehicle much more desirable for customers to own because the charging could be completed in 15 or so minutes instead of many hours. Thus, fast charging might accelerate market penetration if it can be accommodated on the vehicle. However, this practice poses a power challenge, as distinct from an energy challenge, to the grid. Recharging a 10-kWh battery in, say, 15 minutes would require more than 40 kW of power. Larger batteries could impose a power requirement exceeding 50 kW per charge. And since the probable high cost of the early fast chargers would appear to prohibit their use in residences, fast charging would most likely be done in public places and hence while the vehicle is in daily use. Thus fast charging could exacerbate the peak-demand problem in some localities.

Finally, smart-grid technologies applied to the home could enable consumers to manage their vehicle recharging like any other appliance, and respond easily to price signals. The extent to which they adopt and use this capability and the extent to which such response might offset the local challenges posed by plug-in vehicle charging remain unknown.

Technology Uncertainty

In May 2012, eight automotive OEMs announced their adoption of a standard charging system, the Combined Charging System. The standard is a product of the Society of Automotive Engineers (SAE) and the European Automobile Manufacturers' Association (ACEA). Operating under this standard, Combined Charging Systems would integrate the following into one vehicle connector: (1) regular alternating current (ac) charging, (2) fast ac charging, (3) direct current (dc) charging in homes, and (4) ultrafast dc charging. Thus, a Combined Charging System could offer a single-port fast-charging system that still enables plug-in owners with vehicles designed for Level 1 or Level 2 to recharge at public stations. The companies endorsing this system include three U.S. DRIVE members: Chrysler Group LLC, Ford Motor Company, and General Motors Company. The ACEA has asserted that the Combined Charging System will become the standard for all European vehicles by 2017. However, other auto companies, notably Nissan and Mitsubishi, have protested the standard, and Tesla Motors (a U.S. DRIVE partner) has not adopted it.

The technology uncertainty concerns the rate at which the following might occur: (1) the Combined Charging System or some other widely accepted charging standard will be adopted, (2) a new generation of plug-in vehicles able to accept fast charging will appear in the marketplace, and (3) electric utility companies can upgrade transformers, substations, and distribution networks to accommodate the increased power demand.

At the same time, uncertainty exists over the pace of adoption of smart-grid technologies. On the utility side of the meter, smart-grid systems could prove more resilient to unanticipated changes in power demand brought about by fast charging. And on the customer side of the meter, smart micro-grids could manage the recharging of a plug-in vehicle in any prearranged manner. However, the rate of adoption of these technologies cannot be assured to match the rate of adoption of the vehicles.

Policy Uncertainty

The economic incentives for owners to charge their vehicles during times of low grid impact and for electric utility companies or unregulated entities to invest in charging infrastructure fall largely to the utility rate-making authorities in each state. This poses a challenge to achieving the uniformity of national (indeed, international) infrastructure required to support electric vehicle deployment. Here, DOE can exercise its national leadership capabilities to encourage a stable and productive policy environment. This, in turn, would likely reduce the other uncertainties in customer behavior, technology adoption, and infrastructure investment.

A DOE strategy that would exercise leadership from the national perspective will be essential for the prompt and efficient deployment of an electric charging infrastructure. The kind of leadership needed cannot be left to the grid interaction technical team alone. Effective leadership can help clarify the policy environment and lead to more uniform state policies for the build-out of charging infrastructure. Reducing policy uncertainty could, in turn, lower the anxiety felt by prospective plug-in vehicle owners about charging their vehicles in a cost-effective, timely, and environmentally friendly way.

Recommendation 4-8. The senior DOE leadership should consider joining with their counterparts at U.S. DRIVE to work with non-U.S. DRIVE OEMs, equipment suppliers, electric utility leadership, and state regulators to build a uniform and stable policy environment for the deployment of electric charging infrastructure.

RESPONSE TO PHASE 3 RECOMMENDATIONS

> ***NRC Phase 3 Recommendation 4-1.*** *The DOE should broaden the role of the fuel pathways integration technical team (FPITT) to include an investigation of the pathways to provide energy for all three approaches currently included in the Partnership. This broader role could include not only the current technical subgroups for hydrogen but also subgroups on biofuels utilization in advanced internal combustion engines and electricity generation requirements for PHEVs and BEVs, with appropriate industrial representation on each. The role of the parent FPITT would be to integrate the efforts of these subgroups and to provide an overall perspective of the issues associated with providing the required energy in a variety of scenarios that meet future personal transportation needs.* [NRC, 2010, p. 118.]

The Partnership, while recognizing the importance of investigating all three approaches, has elected to maintain the FPITT's focus on hydrogen. The current committee also believes that broader integration and coordination are needed, and it has in fact broadened its recommendation in the current report (current Recommendation 4-1).

> ***NRC Phase 3 Recommendation 4-2.*** *The DOE's Fuel Cell Technologies program and the Office of Fossil Energy should continue to emphasize the importance of demonstrated CO_2 disposal in enabling essential pathways for hydrogen production, especially for coal.* [NRC, 2010, pp. 120-121.]

The DOE responded well to this recommendation in 2010. Although the Office of Fossil Energy and the Office of Fuel Cell Technologies continue to consider carbon when setting program priorities, the post-2010 availability of natural gas as a feedstock has diminished the urgency of demonstrating hydrogen from coal. (See Recommendation 4-3 in the current report.)

> ***NRC Phase 3 Recommendation 4-3.*** *The Fuel Cell Technologies program should adjust its Technology Roadmap to account for the possibility that CO_2 sequestration will not enable a midterm readiness for commercial hydrogen production from coal. It should also consider the consequences to the program of apparent large increases in U.S. natural gas reserves.* [NRC, 2010, p. 121.]

The DOE has indicated that it will add steam reforming of natural gas with cogeneration of steam to the roadmap for midterm readiness in response to the large increases in natural gas, but this option would produce more CO_2 than coal gasification with carbon capture and sequestration. Thus, the response to the recommendation is only partial. The committee believes that other midterm options should be identified.

> ***NRC Phase 3 Recommendation 4-4.*** *The EERE should continue to work closely with the Office of Fossil Energy to vigorously pursue advanced chemical and biological concepts for carbon disposal as a hedge against the inability of geological storage to deliver a publicly acceptable and cost-effective solution in a timely manner. The committee also notes that some of the technologies now being investigated might offer benefits in the small-scale capture and sequestration of carbon from distributed sources.* [NRC, 2010, p. 121.]

The DOE has responded to this recommendation with laboratory and pilot-scale projects to utilize CO_2, including algal production.

> ***NRC Phase 3 Recommendation 4-5.*** *The DOE should continue to evaluate the availability of biological feedstocks for hydrogen in light of the many other claims on this resource—liquid fuels, chemical feedstocks, electricity, food, and others.* [NRC, 2010, p. 121.]

The DOE Biomass Program continues to evaluate the availability of feedstocks for use in various energy and chemical pathways.

> ***NRC Phase 3 Recommendation 4-6.*** *The Partnership should prioritize the many biomass-to-biofuel-to-hydrogen process pathways in order to bring further focus to development in this very broad area.* [NRC, 2010, p. 123.]

The DOE and the hydrogen production technical team continue to evaluate whether biomass-based pathways can meet the hydrogen production cost targets and have conducted an independent review of these costs.

> ***NRC Phase 3 Recommendation 4-7.*** *The Partnership should consider conducting a workshop to ensure that all potentially attractive high-temperature thermochemical cycles have been identified, and it should carry out a systems analysis of candidate systems to identify the most promising approaches, which can then be funded as money becomes available.* [NRC, 2010, p. 123.]

The DOE has conducted analyses of various high-temperature thermochemical cycles and prepared a comprehensive report of the results (Perret, 2011). The report identified significant technical challenges and should be valuable in DOE's program planning.

> ***NRC Phase 3 Recommendation 4-8.*** *The EERE funding for high-temperature thermochemical cycle projects has varied widely and was very low in FY 2009. The committee believes that these centralized production techniques are important, and thus adequate and stable funding for them should be considered.* [NRC, 2010, pp. 123-124.]

The EERE funds three solar thermochemical production projects. The funding in FY 2011 was $1.7 million. The funding level is insufficient to overcome the identified significant technical challenges. The committee believes that DOE should either increase funding consistent with the technical challenges or discontinue the effort.

> ***NRC Phase 3 Recommendation 4-9.*** *Water electrolysis should remain an integral part of the future hydrogen infrastructure development. The DOE should continue to fund novel water electrolysis materials and methods, including alternative membranes, alternative catalysts, high-temperature and -pressure operation, advanced engineering concepts, and systems analysis. Additional efforts should be placed on advanced integration concepts in which the electrolyzer is co-engineered with subsequent upstream and downstream unit operations to improve the overall efficiency of a stand-alone system.* [NRC, 2010, p. 126.]

In general, DOE's program is responsive to this recommendation, particularly in view of budget constraints and limitations on other high-priority programs. Existing programs continue to address the membranes, components, and operation of the electrolysis technologies, all consistent with the recommendation.

> ***NRC Phase 3 Recommendation 4-10.*** *Commercial demonstrations should be encouraged for new designs based on established electrolytic processes. For newer concepts such as high-temperature solid oxide systems, efforts should remain focused on laboratory evaluations of the potential for lifetime and durability, as well as on laboratory performance assessments.* [NRC, 2010, p. 126.]

Prototype-scale demonstrations are planned as funding allows. SunHydro filling stations along the East Coast are recent commercial demonstrations of Proton's electrolytic process, and electrolytic technologies developed with EERE funding by Proton, Giner, and Avalence are installed at NREL for an independent assessment. The response was appropriate, given existing budget constraints.

> ***NRC Phase 3 Recommendation 4-11.*** *Work on close coupling of wind and solar energy with electrolysis should be continued with stable funding. Further improvements in electrolyzers, including higher stack pressure, and in power electronics will benefit this application.* [NRC, 2010, p. 126.]

Work at NREL is responsive to this recommendation. The Wind2H2 project is evaluating the integration of EERE-funded improved electrolytic technologies with wind and solar resources.

> ***NRC Phase 3 Recommendation 4-12.*** *The Partnership should examine the goals for the photolytic approach to producing hydrogen using microorganisms and formulate a vision with defined targets. Otherwise, this approach should be deemphasized as an active research area for hydrogen production.* [NRC, 2010, p. 128.]

The DOE has responded to this recommendation with analyses of biological and photochemical hydrogen production, leading to prioritization of R&D focused on photolytic technologies.

> ***NRC Phase 3 Recommendation 4-13.*** *Hydrogen delivery, storage, and dispensing should be based on the program needed to achieve the cost goal for 2017. If it is not feasible to achieve that cost goal, emphasis should be placed on those areas that would most directly impact the 2015 decision regarding commercialization. In the view of the committee, pipeline, liquefaction, and compression programs are likely to have the greatest impact in the 2015 time frame. The cost target should be revised to be consistent with the program that is carried out.* [NRC, 2010, p. 129.]

The DOE has been responsive by updating the technical targets and revising its cost target (as discussed further in Chapter 4 in the current report).

> ***NRC Phase 3 Recommendation 4-14.*** *A thorough systems analysis of the complete biofuel distribution and end-use system should be done. This should include (1) an analysis of the fuel- and engine-efficiency gains possible through ICE technology development with likely particular biofuels or mixtures of biofuels and conventional petroleum fuels, and (2) a thorough analysis of the biofuel distribution system needed to deliver these possible fuels or mixtures to the end-use application.* [NRC, 2010, p. 132.]

The response from DOE to item 1 in the recommendation is adequate. There is no response to item 2 other than saying that it is the responsibility of the Biomass Program rather than that of the FreedomCAR and Fuel Partnership. The purpose of the recommendation was to formalize a structure to help develop answers to this complicated system involving the engine, the biofuel quality, and the fuel distribution system. Given the partial response, the committee cannot determine the extent to which that purpose has been fulfilled.

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5

Adequacy and Balance of the Partnership

Included in the previous chapters is an assessment of the status, progress, and barriers facing the various technologies that are under development by the U.S. DRIVE Partnership, which has evolved from its predecessor, the FreedomCAR and Fuel Partnership. Overall, technical progress has been steady and, in some cases, impressive. This chapter focuses on the adequacy and balance of the Partnership, including a review of and comments on budgetary resources and levels of effort expended toward each of the major budget line items.

In the three previous National Research Council (NRC) reports (NRC, 2005, 2008, 2010), the NRC reviewed the funding for the FreedomCAR and Fuel Partnership and the allocation related to that funding between hydrogen-related and non-hydrogen-related activities. Generally speaking, those earlier reviews concluded that the balance between technologies was largely appropriate. However, in the NRC (2010) Phase 3 report, it was noted that major shifts in emphasis and funding had occurred in the most recent 12 months. Those shifts and their continuation are explored in this chapter.

Since the beginning of the Partnership (U.S. DRIVE and its predecessor) and even earlier during the Partnership for a New Generation of Vehicles (PNGV) program, the NRC reviews have recommended government support emphasizing long-term, high-risk, high-payoff technologies. It was and is the view of the committee that this is an appropriate expenditure of government resources. However, recent economic conditions, including the need for government support to prevent the collapse of two major automobile manufacturers, influence what the committee and the government consider "appropriate." It is still believed by the committee that support for precompetitive research on long-term technologies such as the enablers for hydrogen to become a viable transportation fuel and the fuel cell research and development (R&D) leading to affordable hydrogen fuel cell vehicles (HFCVs) is important and should be continued. At the same time, the committee continues to agree that government support for technologies that have impact both in nearer and longer terms, especially those that could transfer some of the required transportation energy from petroleum to biofuels or to the electric grid, is also appropriate.

Historically, hydrogen-related activities represented approximately 70 percent of the DOE funding supporting technology development. This emphasis was consistent with the recommendations of prior NRC reports (e.g., *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* [NRC/NAE, 2004]) and the U.S. Department of Energy's (DOE's) *Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan* (DOE, 2004). It was also consistent with continuation of President George W. Bush's commitment to the funding of the first 5 years of the FreedomCAR and Fuel Partnership. However, as discussed in the NRC (2010) Phase 3 report, early in 2010 all initial funding requests for hydrogen-related activities for vehicles were withdrawn (although subsequently reinstated). The reasons given for this were that four major breakthroughs were required to achieve commercialization of HFCVs, and it was deemed highly unlikely that all four could be simultaneously achieved. The four major hurdles cited were the sustainable production of hydrogen, effective distribution, onboard hydrogen storage, and reliable low-cost fuel cells.

The NRC (2010) Phase 3 report noted that these four challenges are indeed huge, but also stated the belief that the other two possible pathways to achieving the ultimate Partnership goals of significant reduction of petroleum use and of emissions—namely, vehicles using biofueled internal combustion engines (ICEs) and highly electrified vehicles (e.g., plug-in hybrid electric vehicles [PHEVs] and battery electric vehicles [BEVs])—also face major challenges. The NRC Phase 3 review concluded that research on all three pathways deserved continued funding for the immediate future (see NRC, 2010, Appendix B, the Phase 3 interim letter report).

Since that time, the pattern of rebalancing the funding portfolio has continued. The share of DOE funding devoted to hydrogen activities has dropped from an FY 2009 total of $200 million to the FY 2012 total of $104 million, as shown in Table 5-1. Over the same period, battery R&D funding in the Vehicle Technologies Program (VTP) related to U.S. DRIVE Partnership efforts rose from $69 million to $90 million and from $23 million to $31 million for advanced combustion R&D (see Table 5-2). The relevant VTP budget has been steadily increasing, as shown in Table 5-2, growing from $174 million in FY 2009 to $238 million in FY 2012. As noted in the NRC (2010) Phase 3 report, other vehicle technologies receiving significant funding, such as more efficient electrical components

TABLE 5-1 Fuel Cell Technologies Program Funding Distribution, FY 2009 Through FY 2012

	FY 2009 ($)	FY 2010 ($)	FY 2011 ($)	FY 2012 ($)
Fuel Cell R&D	80,067,500	75,608,830	41,916,000	43,622,000
Rescission	0	0	0	188,000
SBIR and STTR	2,232,500	1,873,170	1,084,000	1,190,000
TOTAL FUEL CELL R&D	82,300,000	77,482,000	43,000,000	45,000,000
Production and Delivery R&D	10,000,000	14,601,000	17,521,000	16,918,000
Rescission	0	0	0	94,000
SBIR and STTR	0	399,000	479,000	488,000
TOTAL PRODUCTION AND DELIVERY	10,000,000	15,000,000	18,000,000	17,500,000
Hydrogen Storage R&D	57,823,000	31,149,000	14,601,000	16,918,000
Rescission	0	0	0	94,000
SBIR and STTR	1,377,000	851,000	399,000	488,000
TOTAL HYDROGEN STORAGE R&D	59,200,000	32,000,000	15,000,000	17,500,000
Technology Validation	14,789,000	13,005,000	8,988,000	8,986,000
SBIR and STTR	211,000	92,000	12,000	14,000
TOTAL TECHNOLOGY VALIDATION	15,000,000	13,097,000	9,000,000	9,000,000
Safety, Codes and Standards	12,237,500	8,653,000	6,790,000	6,938,000
SBIR and STTR	262,500	186,000	210,000	62,000

TOTAL SAFETY, CODES AND STANDARDS	12,500,000	8,839,000	7,000,000	7,000,000
Systems Analysis	7,520,000	5,408,000	3,000,000	3,000,000
SBIR and STTR	192,825	148,000	0	0
TOTAL SYSTEMS ANALYSIS	7,712,825	5,556,000	3,000,000	3,000,000
Manufacturing R&D	4,480,000	4,867,000	2,920,000	1,944,000
SBIR and STTR	519,675	133,000	80,000	56,000
TOTAL MANUFACTURING R&D	4,999,675	5,000,000	3,000,000	2,000,000
Market Transformation	4,747,000	15,005,000	0	3,000,000
SBIR and STTR	0	21,000	0	0
TOTAL MARKET TRANSFORMATION	4,747,000	15,026,000	0	3,000,000
Education	4,200,000	2,000,000	0	0
SBIR and STTR	0	0	0	0
TOTAL EDUCATION	4,200,000	2,000,000	0	0
FUEL CELL TECHNOLOGIES TOTAL	200,659,500	174,000,000	98,000,000	104,000,000

NOTE: Acronyms are defined in Appendix E.

SOURCE: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

TABLE 5-2 FY 2009 Through FY 2012 DOE Vehicle Technologies Program Budget Distribution and Estimated Funds for Projects Related to U.S. DRIVE (or FreedomCAR) and 21st Century Truck Partnership (21CTP) Goals (New Structure-Prior Years Comparable) ($ thousands)

FY 2011 DOE Budget Structure	FY 2009 Comparable Approp. with SBIR	FY 2009 Freedom CAR	FY 2009 21CTP	FY 2009 Other	FY 2010 Comparable Approp. with SBIR	FY 2010 Freedom CAR	FY 2010 21-CTP	FY 2010 Other
Batteries and elec. drive technol. Tech Val					0	0	0	0
Energy Storage R&D	69,425	69,425	0	0	76,271	76,271	0	0
APEEM	17,358	17,358	0	0	22,295	22,295	0	0
SBIR/STTR	2,713			2,713	2,839		0	2,839
B&EDT Total	89,496	86,783	0	2,713	101,405	98,566	0	2,839
Vehicle sys. simula. & testing (VSST)	21,126	18,210	2,916	0	43,732	38,232	5,500	0
SBIR/STTR	298			298	596			596
VSST Total								
Adv. combus. eng. R&D	21,424	18,210	2,916	298	44,328	38,232	5,500	596
Combus. and Emission Control	35,089	22,647	12,442	0	47,239	28,817	18,422	0
SS Energy Conversion (formerly Waste Heat Recovery)	4,568	2,780	1,788	0	8,748	6,221	2,527	0
SBIR/STTR	1,143	0	0	1,143	1,613	0	0	1,613
Adv. Combus. Eng. R&D Total								
Materials technol.	40,800	25,427	14,230	1,143	57,600	35,038	20,949	1,613
Propulsion Materials Tech.	10,742	5,882	4,860	0	12,989	7,344	5,645	0
Lightweight Materials Technol.	22,374	22,374	0	0	30,652	30,652	0	0
HTML	5,670	0	0	5,670	5,662	0	0	5,662
SBIR/STTR	1,117	0	0	1,117	1,420	0	0	1,420
Materials Technol. Total								
Fuels technol.	39,903	28,256	4,860	6,787	50,723	37,996	5,645	7,082
Adv. Petrol.-Based Fuels	5,808	3,475	2,333	0	6,780	3,961	2,819	0
Non-Petrol.-Based Fuels & Lubes	13,751	9,720	4,031	0	16,641	11,463	5,178	0
SBIR/STTR	563			563	674			674
Fuels Technol. Total	20,122	13,195	6,364	563	24,095	15,424	7,997	674

				Preliminary FY 2012 Plan—Subject to Change			
FY 2011 Congress Request with SBIR	FY 2011 U.S. DRIVE	FY 2011 21CTP	FY 2011 Other	FY 2012 Final Approp. with SBIR	FY 2012 Planned U.S. DRIVE	FY 2012 Planned 21CTP	FY 2012 Planned Other
0	0	0	0	0	0	0	0
81,549	81,549	0	0	89,934	89,934	0	0
21,614	21,614	0	0	27,806	27,806	0	0
2,972		0	2,972	3,579		0	3,579
106,135	103,163	0	2,972	121,319	117,740	0	3,579
42,647	30,047	12,600	0	47,198	34,598	12,600	0
581	0	0	581	635			635
43,228	30,047	12,600	581	47,833	34,598	12,600	635
47,239	29,500	17,739	0	49,320	30,799	18,521	0
8,748	8,000	748	0	8,707	8,000	707	0
1,613	0	0	1,613	1,764			1,764
57,600	37,500	18,487	1,613	59,791	38,799	19,228	1,764
12,989	6,108	6,881	0	12,576	5,914	6,662	$0
29,097	26,977	2,120	0	27,284	25,164	2,120	$0
5,662	0	0	5,662	970	0	0	970
1,375	0	0	1,375	1,241	0	0	1,241
49,123	33,085	9,001	7,037	42,071	31,078	8,782	2,211
0	0	0	0	0			
10,692	5,835	4,857	0	17,904	9,771	8,133	0
308	0	0	308	544			544
11,000	5,835	4,857	308	18,448	9,771	8,133	544

continues

TABLE 5-2 Continued

FY 2011 DOE Budget Structure	FY 2009 Comparable Approp. with SBIR	FY 2009 Freedom CAR	FY 2009 21CTP	FY 2009 Other	FY 2010 Comparable Approp. with SBIR	FY 2010 Freedom CAR	FY 2010 21-CTP	FY 2010 Other
Outreach, deploy. & analysis (OD&A)	950	950	0	0	1,000	1,000	0	0
Adv. Vehicle Competitions	1,750	1,750	0	0	2,000	2,000	0	0
Education					0	0	0	0
Safety, Codes and Standards					0	0	0	0
Legislative and Rulemaking	1,804	0	0	1,804	2,004	0	0	2,004
VT Deployment	25,000	0	0	25,000	25,510	0	0	25,510
Biennial Peer Reviews	500	0	500	0	2,700	500	0	2,200
VMT Reduction & Legacy Fleet Improvement	0	0	0	0	0	0	0	0
SBIR/STTR	262	0	0	262	0	0	0	0
OD&A Total	30,266	2,700	500	27,066	33,214	3,500	0	29,714
Vehicle Technol. Total	242,011	174,571	28,870	38,570	311,365	228,756	40,091	42,518

NOTE: The following Fuel Cell line items were part of the Vehicle Technology Program (VTP) in FY 2009 but were transferred back to Hydrogen Fuel Cell Technologies (HFCT) in FY 2010: Technology Validation, $14,789; Safety, Codes and Standards, $12,238; Education, $4,200. Shaded areas indicate a name or structure change that began with the 2011 budget request. All budgets are shown in the 2011 structure. Acronyms are defined in Appendix E. Estimated budgets were received by the committee from DOE in early 2012 and may have changed since that time.

and lighter-weight materials, would all potentially benefit all future propulsion systems and are therefore judged worthwhile.

The recipients of DOE's FY 2012 funds by sector (national laboratories, industry, academia, etc.) are shown in Figure 5-1. The pattern is broadly similar to that in prior years (see NRC, 2010, Figures 5-1 and 5-2).

The trend continues in the FY 2013 Office of Energy Efficiency and Renewable Energy (EERE) budget request illustrated in Table 5-3, with hydrogen activities (Fuel Cell Technologies Program [FCTP]) allocated $80 million (a reduction of 23 percent), while the VTP overall is allocated $420 million (an increase of almost 28 percent over the equivalent FY 2012 total of $329 million), including a 75 percent increase for battery R&D.

Toward the end of the period covered by the NRC Phase 3 report, another major initiative related to U.S. DRIVE Partnership goals emerged. That was the American Recovery and Reinvestment Act (ARRA) of 2009 and its massive funding of advanced technologies under the umbrella of economic stimulus. This

				Preliminary FY 2012 Plan—Subject to Change			
FY 2011 Congress Request with SBIR	FY 2011 U.S. DRIVE	FY 2011 21CTP	FY 2011 Other	FY 2012 Final Approp. with SBIR	FY 2012 Planned U.S. DRIVE	FY 2012 Planned 21CTP	FY 2012 Planned Other
1,000	1,000	0	0	995	995	0	0
2,000	2,000	0	0	1,991	1,991	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
2,004	0	0	2,004	1,992	0	0	1,992
27,410	0	0	27,410	27,876	0	0	27,876
500	500	0	0	3,500	500	0	3,000
0	0	0	0	2,912	2,912		
0	0	0	0	79	0	0	79
32,914	3,500	0	29,414	39,345	6,398	0	32,947
300,000	213,130	44,945	41,925	328,807	238,384	48,743	41,680

expenditure is entirely separate from the U.S. DRIVE Partnership funding, but many of its initiatives are directly relevant to technology development activities within the Partnership. Of the ARRA funds assigned to DOE, $2.4 billion was allocated to vehicle electrification, including $1.4 billion for lithium-ion battery manufacture (and $100 million for other battery technologies), $500 million for electric drive component manufacturing, and $400 million for transportation electrification. (A modest share [1.5 percent] of the DOE ARRA funds was also allocated to support fuel cell purchases for non-automotive use, and this could have an indirect benefit to the U.S. DRIVE goals.)

As noted above, the ARRA-funded activities are beyond the purview of Partnership leadership or this committee, and DOE biofuel activity is also outside the Partnership, but it is nonetheless clear that taken together, VTP and ARRA funding represent a substantial emphasis on hybrid and battery electric vehicles, without concomitant emphases on the other two potential pathways to achieving Partnership and national transportation energy goals referenced above.

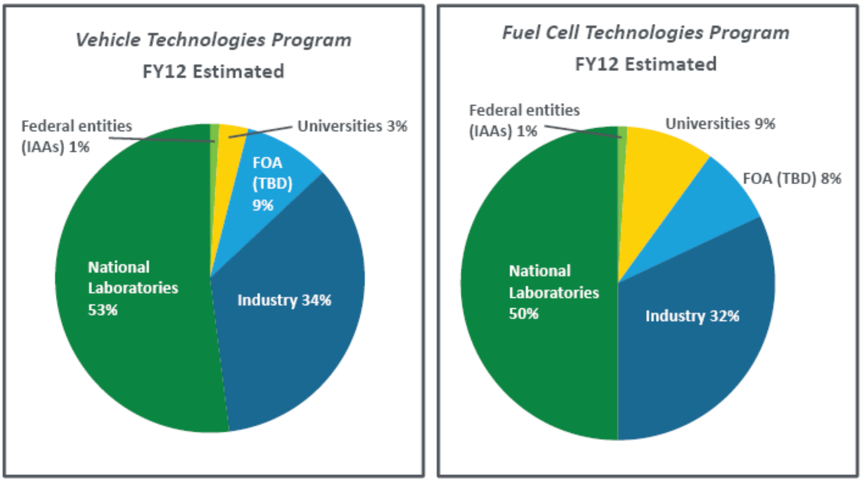

FIGURE 5-1 Department of Energy's Office of Energy Efficiency and Renewable Energy planned program funding, by organization, FY 2012 (estimated). NOTE: IAA, Interagency Agreement; FOA (TBD), Funding Opportunity Announcement (to be determined). SOURCE: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

Adequacy and balance of the program depend on what the program intends to achieve and when. Reducing dependence on petroleum and reducing emissions are goals that are broad and nonspecific and not readily amenable to the setting of priorities. In that regard, engaging the Partnership's Executive Steering Group to set clearer targets would be desirable in order to provide a framework for ranking technology readiness and for assessing the seriousness of hurdles and evaluating them against potential societal benefits over time. As an example, the National Academies' report *America's Energy Future: Technology and Transformation* (NAS/NAE/NRC, 2009) laid out a scenario of 2 to 4 percent electrified vehicles (PHEVs and BEVs) and 0 to 1 percent HFCVs by 2020, and 10 to 25 percent and 3 to 6 percent, respectively, by 2035. In order to achieve the projected volumes by 2035, significant improvements in battery performance are needed to make the vehicles attractive to the consumer. Extrapolating from current technologies without successful development of new chemistry, electric drive vehicles are more attractive than fuel cell vehicles for short-range usage, but less so for long-range travel. Thus, a large-scale replacement of petroleum usage by these alternate fuels will potentially rely on both technologies to satisfy consumer needs. It is appropriate to continue investing resources on the most impactful research in order to achieve these targets, and it is important to focus resources within each technology area on the greatest technical challenges (as discussed in Chapter 3), and also not to let the resource dwindle so far as to be unable to sustain a critical mass required to support a robust decision on any technology.

TABLE 5-3 Office of Energy Efficiency and Renewable Energy (EERE) Budget Summary, FY 2011 Through FY 2013 (Request)

Programs	FY 2011 Current ($ thousands)	FY 2012 Enacted ($ thousands)	FY 2013 Request ($ thousands)	FY 2013 vs FY 2012 ($ Change)	FY 2013 vs FY 2012 (% Change)
Renewable Energy					
Biomass and Biorefinery R&D	179,979	199,276	270,000	70,724	35.49
Geothermal Technology	36,992	37,862	65,000	27,138	71.68
Hydrogen and Fuel Cell Technologies	95,847	103,624	80,000	(23,624)	–22.80
Solar Energy	259,556	288,951	310,000	21,049	7.28
Water Power	29,201	58,787	20,000	(38,787)	–65.98
Wind Energy	78,834	93,254	95,000	1,746	1.87
Energy Efficiency					
Advanced Manufacturing	105,899	115,580	290,000	174,420	150.91
Building Technologies	207,310	219,204	310,000	90,796	41.42
Federal Energy Management Program	30,402	29,891	32,000	2,109	7.06
Vehicle Technologies	293,151	328,807	420,000	91,193	27.73
Weatherization and Intergovernmental	231,300	128,000	195,000	67,000	52.34
Corporate					
Facilities and Infrastructure	51,000	26,311	26,400	89	0.34
Program Direction	170,000	165,000	164,700	(300)	–0.18
Strategic Programs	32,000	25,000	58,900	33,900	135.60
Subtotal, EERE	1,801,471	1,819,547	2,337,000		
Use of Prior-Year Balances	(29,750)	(9,909)	0		
Cancellation of Prior-Year Balances	0	0	(69,667)		
TOTAL, EERE	1,771,721	1,809,638	2,267,333		

NOTE: Numbers in parentheses signify the amount by which funding was reduced. SOURCE: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

RECOMMENDATION

Recommendation 5-1. The Executive Steering Group should be engaged to set targets for the U.S. DRIVE Partnership that are consistent with the objectives of reduced petroleum consumption and greenhouse gas emissions, and U.S. DRIVE should conduct an overall review of the Partnership portfolio, both for the adequacy of the R&D effort to achieve the targets and for focus on the mission of supporting longer-term, higher-risk precompetitive activities in all three potential primary pathways.

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Appendixes

A

Biographical Sketches of Committee Members

Vernon P. Roan, *Chair,* is retired director of the Center for Advanced Studies in Engineering and professor of mechanical engineering at the University of Florida, where he has been a faculty member for more than 30 years. Since 1994, he has also been the director of the University of Florida Fuel Cell Research and Training Laboratory. He has developed improved modeling and simulation systems for a fuel cell bus program and worked as a consultant to Pratt and Whitney on advanced gas-turbine propulsion systems. Previously, he was a senior design engineer with Pratt and Whitney Aircraft. Dr. Roan has more than 25 years of research and development experience. His research at the University of Florida has involved both spark-ignition and diesel engines operating with many alternative fuels and advanced concepts. With groups of engineering students, he designed and built a 20-passenger diesel-electric bus for the Florida Department of Transportation and a hybrid-electric urban car using an internal combustion engine and lead-acid batteries. He has been a consultant to the Jet Propulsion Laboratory (JPL), monitoring JPL's electric and hybrid vehicle programs. He has organized and chaired two national meetings on advanced vehicle technologies and a national seminar on the development of fuel-cell-powered automobiles and has published numerous technical papers on innovative propulsion systems. He was one of the four members of the Fuel Cell Technical Advisory Panel of the California Air Resources Board (CARB), which issued a report in May 1998 regarding the status and outlook for fuel cells for transportation applications. He also served on the CARB Expert Panel on Zero Emission Vehicles, which issued a report in 2007. He has served on numerous National Research Council committees, including the Committee on the Research Program of the FreedomCAR and Fuel Partnership, Phase 1, Phase 2, and Phase 3, and the prior committee on review of the Partnership for a New Generation of Vehicles. Dr. Roan received his B.S. in aeronautical engineering and his M.S. in engineering from the University of Florida and his Ph.D. in engineering from the University of Illinois.

R. Stephen Berry (NAS) is the James Franck Distinguished Service Professor Emeritus of Chemistry at the University of Chicago and holds appointments in the College, the James Franck Institute, and the Department of Chemistry. He has also held an appointment in the School of Public Policy Studies at the University of Chicago and has worked on a variety of subjects ranging from strictly scientific matters to a variety of topics in policy. He spent 1994 at the Freie Universität Berlin as an awardee of the Humboldt Prize. In 1983 he was awarded a MacArthur Fellowship. His experimental research includes studies of negative ions, chemical reactions, detection of transient molecular species, photoionization, and other laser-matter interactions. Other research has involved interweaving thermodynamics with economics and resource policy, including efficient use of energy. Since the mid-1970s, Dr. Berry has worked on issues of science and the law, and with management of scientific data, activities that have brought him into the arena of electronic media for scientific information and issues of intellectual property in that context. Dr. Berry is a member of the National Academy of Sciences. He attended Harvard University, where he received an A.B. and an A.M. in chemistry and a Ph.D. in physical chemistry.

David L. Bodde serves as a professor and senior fellow at Clemson University. Prior to joining Clemson University, Dr. Bodde held the Charles N. Kimball Chair in Technology and Innovation at the University of Missouri in Kansas City. Dr. Bodde serves on the board of directors of several energy and technology companies, including Great Plains Energy, and the Commerce Funds. His executive experience includes the following: vice president, Midwest Research Institute; president, MRI Ventures; assistant director, Congressional Budget Office; and deputy assistant secretary in the U.S. Department of Energy. He has served as a member of the NRC's Board on Energy and Environmental Systems, the Committee on Alternatives and Strategies for Future Hydrogen Production and Use, and the Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies. He has a doctorate in business administration from Harvard University, M.S. degrees in nuclear engineering (1972) and management (1973), and a B.S. from the United States Military Academy.

Kathryn Bullock is the president and founder of Coolohm, Inc., which is a technical consulting company that specializes in direct current (dc) power sources such as batteries, capacitors, and fuel cells and their application in electronic systems. She is also an adjunct faculty member at Villanova University, where she teaches a course on electrochemical power sources, including fuel cells, batteries, and capacitors and their application in dc power systems. Her previous positions include vice president, C&D Technologies, Inc., where she was responsible for the development of new battery products and new product applications such as solar energy and fuel cell systems and for providing technical leadership and support to executive and board members; development manager, Power Sources, Medtronic, Inc., Promeon Division; technical manager, Batteries and Purchased Products, Lucent Technologies, Bell Laboratories (Mesquite, Texas); and manager, Chemical Research Department, and senior electrochemist, Electrochemical Research Department, Johnson Controls, Inc. She has extensive research and development and manufacturing experience in electrochemical devices, including batteries and capacitors. She has a Ph.D. in physical chemistry and an M.S. in chemistry from Northwestern University, and a B.A. in English from the University of Colorado.

Dennis A. Corrigan is the founder and president of DC Energy Consulting, LLC, and has been on the research faculty of Wayne State University for the past several years, including during a 2011 Intergovernmental Personnel Act (IPA) assignment to the U.S. Army Tank and Automotive Research, Development, and Engineering Center (TARDEC) where he served as chief energy strategist. His career has focused on electrochemical energy conversion devices for electric and hybrid vehicle applications. His research and development experience spans a wide range, from fundamental materials research at the atomic level to the integration of full systems in vehicular applications, for more than 12 years at GM Research Labs and 16 years at Energy Conversion Devices (ECD Ovonics). He has had direct experience with lead-acid, nickel-zinc, nickel-metal hydride, and lithium batteries, as well as proton exchange membrane and alkaline fuel cells and supercapacitors, and the integration of electrochemical power systems into electric and hybrid vehicles. More recently, Dr. Corrigan developed graduate engineering courses on automotive batteries and fuel cells as well as the base introductory course on hybrid and electric vehicles for Wayne State University's new electric drive vehicle engineering curriculum. He has a B.S. in chemistry from Purdue University and a Ph.D. in electrochemistry from the University of Wisconsin. He has contributed more than 60 technical publications, 100 presentations, and three edited books and has 19 issued U.S. patents. Dr. Corrigan has served many years as an officer of the Detroit Section of the Electrochemical Society, including three terms as chair.

Glenn A. Eisman is a principal partner at Eisman Technology Consultants, LLC; a managing partner at H2Pump, LLC; and an adjunct professor at Rensselaer Polytechnic Institute in materials science and engineering (Troy, N.Y.) and at the Graduate College of Engineering at Union University (Schenectady, N.Y.). His previous positions include chief technology officer, Plug Power, Inc.; technical leader, the Advanced Materials Program, Central Research and New Businesses, Dow Chemical Company; project leader, Discovery Research R&D and Inorganic Chemical Research, Dow Chemical Company; and Robert A. Welch Research

Fellow, University of Texas-Austin. Dr. Eisman has 30 years of experience in research and development and product development on fuel cells, hydrogen technologies, electrochemical engineering, physical and inorganic solid-state chemistry, and new technology commercialization and business development. He received the Inventor of the Year Award, Dow Chemical Co., in 1993. He earned a bachelor's degree in chemistry from Temple University and a Ph.D. in physical inorganic chemistry from Northeastern University. He has published more than 20 technical papers and has been awarded more than 20 U.S. patents.

W. Robert Epperly is an independent consultant. From 1994 to 1997, he was the president of Catalytica Advanced Technologies, Inc., a company developing new catalytic technologies for the petroleum and chemical industries. Prior to joining Catalytica, he was the general manager of Exxon Corporate Research and earlier had been the director of the Exxon Fuels Research Laboratory. After leaving Exxon, he was the chief executive officer of Fuel Tech N.V., a company developing new combustion and air pollution control technology. Mr. Epperly has authored or co-authored more than 50 publications on technical and managerial topics, including two books, and has 38 U.S. patents. He has extensive experience in the conversion of fossil feedstocks to alternative fuels such as gases and liquids, fuels, catalysis, air pollution control, and research and development management. He received an M.S. degree in chemical engineering from Virginia Polytechnic Institute and State University.

David E. Foster is the Phil and Jean Myers Professor of Mechanical Engineering at the University of Wisconsin-Madison. He received his B.S. and M.S. degrees in mechanical engineering from the University of Wisconsin-Madison in 1973 and 1975, respectively. He received his Ph.D. in mechanical engineering in 1979 from the Massachusetts Institute of Technology. He has been a faculty member at the University of Wisconsin since completion of his Ph.D. He teaches and conducts research in the areas of thermodynamics, fluid mechanics, and chemical kinetic and emission formation processes in internal combustion engines. He is an active member of the Engine Research Center, of which he served as the director from 1994 through 1999, and as of September 2008 is again serving as director. He is also the co-director of the General Motors-ERC Collaborative Research Laboratory, a collaborative research effort between General Motors Research and the Engine Research Center that was established in 2003. Professor Foster is a recipient of the Ralph R. Teetor Award, the Forest R. McFarland Award, and multiple Lloyd L. Withrow Distinguished Speaker Awards of the Society of Automotive Engineers. Professor Foster is a registered professional engineer in the state of Wisconsin and has won departmental, engineering society, and university awards for his classroom teaching. He was a member of the National Research Council's Partnership for a New Generation of Vehicles review committee for 6 years and has served on the NRC Committee to Assess Fuel Economy Technologies of Medium- and Heavy-Duty Vehicles, the NRC Committee on Review of the FreedomCAR and Fuel Research Program, and the Committee to Review the 21st Century Truck Partnership. He has been awarded an Academic Contribution Award from the Japan Society of Automotive Engineers (JSAE) and a Honda Gold Medal from the American Society of Mechanical Engineers for outstanding contributions in the field of personal transportation, and he is a fellow of the Society of Automotive Engineers.

Gerald Gabrielse (NAS) is Leverett Professor of Physics at Harvard University. His previous positions include assistant and associate professor at the University of Washington-Seattle and chair of the Harvard Physics Department. His physics research focuses on making the most accurate measurements of the electron magnetic moment and the fine structure constant, and on precise laser spectroscopy of helium. Professor Gabrielse also leads the International ATRAP Collaboration, whose goal is accurate laser spectroscopy with trapped antihydrogen atoms. His many awards and prizes include fellow of the American Physical Society, Davisson-Germer Prize of the American Physical Society, the Humboldt Research Award (Germany, 2005), and the Tomassoni Award (Italy, 2008). Harvard University awarded Professor Gabrielse both its George Ledlie Research Prize and its Levenson Teaching Prize. Hundreds of outside lectures include a Källén Lecture (Sweden), a Poincaré Lecture (France), a Faraday Lecture (Cambridge, U.K.), a Schrodinger lecture (Austria), a Zachariasen Lecture (University of Chicago), and a Rosenthal Lecture (Yale University). He is a member of the National Academy of Sciences. He has a B.S. from Calvin College and an M.S. and a Ph.D. in physics from the University of Chicago.

Linos Jacovides (NAE) retired as the director of Delphi Research Labs, a position that he held from 1998 to 2007. Dr. Jacovides joined General Motors Research and Development in 1967 and became department head of electrical engineering in 1985. His areas of research were the interactions between power electronics and electrical machines in electric vehicles and locomotives. He later transitioned to Delphi with a group of researchers from GM to set up the Delphi Research Laboratories. He is a fellow of both the Institute of Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers; he was president of the Industry Applications Society of IEEE in 1990. He received a B.S. degree in electrical engineering and an M.S in machine theory from the University of Glasgow, Scotland, in 1961 and 1962, respectively. He received his Ph.D. in generator control systems from the Imperial College, University of London, in 1965.

Harold H. Kung is professor of chemical engineering and director of the Center for Energy Efficient Transportation at Northwestern University. His areas of research include surface chemistry, catalysis, electrical energy storage, and chemical reaction engineering. His professional experience includes work as a research chemist at E.I. du Pont de Nemours & Co., Inc. He is a recipient of the P.H. Emmett Award and the Robert Burwell Lectureship Award from the North American Catalysis Society, the Herman Pines Award of the Chicago Catalysis Club, the G.A. Somorjai Award of the American Chemical Society, and the E. Thisele Award of the American Institute of Chemical Engineers, Chicago Section. He is an editor of *Applied Catalysis A: General*. He has a Ph.D. in chemistry from Northwestern University.

Gene Nemanich is the retired vice president of Hydrogen Systems for Chevron Technology Ventures where he was responsible for hydrogen supply and developing and commercializing new hydrogen technologies. He has 32 years of experience with integrated oil companies, including Exxon, Cities Service, Texaco, and Chevron. He has also worked in the areas of refining, clean coal technology, oil supply and trading, and research leading to the development of new hydrogen systems. He represented Texaco in the California Fuel Cell Partnership in 2000-2001 and was a director of Texaco Ovonic Hydrogen Systems LLC, a joint venture with Energy Conversion Devices to commercialize metal hydride hydrogen storage systems. He was one of seven industry leaders who helped prepare the Department of Energy-sponsored Hydrogen Roadmap, and he has served as chair of the National Hydrogen Association. He has served on several National Research Council committees, including those on the Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, Transitions to Alternative Transportation Technologies—A Focus on Hydrogen and Plug-in Hybrid Electric Vehicles, and the FreedomCAR and Fuel Partnership Phase 3 Review. He has a B.S. in chemical engineering from the University of Illinois and an M.B.A. from the University of Houston.

Robert J. Nowak is a consultant in the areas of advanced energy storage and conversion. He has directed and supported research in fuel cells, batteries, capacitors, energy harvesting, fuel processing, thermal energy conversion, micro-engines, hydrogen storage, biofuel cells, sonoluminescence, and biomolecular motors. He has served on several National Research Council (NRC) committees. He received his B.A. and M.S. degrees in chemistry from Oakland University and his Ph.D. degree in chemistry from the University of Cincinnati. He was selected as NRC Postdoctoral Fellow at the Naval Research Laboratory in 1979 and worked there as a staff member until 1986. He was a program manager at the Office of Naval Research (1986-1996) and the Defense Advanced Research Projects Agency (1996-2002).

Bernard Robertson (NAE) is president of BIR1, LLC, an engineering consultancy specializing in transportation and energy matters that he founded in January 2004, upon his retirement from DaimlerChrysler Corporation. During the latter part of his 38-year career in the automotive industry, Mr. Robertson was elected an officer of Chrysler Corporation in February 1992. He was appointed senior vice president coincident with the merger of Chrysler Corporation and Daimler-Benz AG in November 1998, and was named senior vice president of engineering technologies and regulatory affairs in January 2001. In his last position, he led the Liberty and Technical Affairs Research Group; Advanced Technology Management and FreedomCAR activities; and hybrid electric, battery electric, fuel cell, and military vehicle development. In addition, he was responsible for regulatory analysis and compliance for safety and emissions. Mr. Robertson holds an M.B.A. degree from Michigan State University, a master's degree in automotive engineering from the Chrysler Institute, and a master's degree in mechanical sciences from Cambridge University, England. He is a member of the National Academy of Engineering, a fellow of the Institute of Mechanical Engineers (U.K.), a Chartered Engineer (U.K.), and a fellow of the Society of Automotive Engineers.

Constantine Samaras is an engineer at the RAND Corporation, a professor at the Pardee RAND Graduate School, and an adjunct assistant professor of engineering and public policy at Carnegie Mellon University. He researches how policy actions and research and development investments affect energy pathways and security, infrastructure requirements, economic and innovation outcomes, and life-cycle environmental impacts. He has extensive experience analyzing advanced technology deployment in the transportation and electricity systems and has published studies exploring the life-cycle environmental, economic, and policy aspects of electric vehicles, hydrogen, and biomass, as well as renewable and conventional electricity and fuels. He received a Ph.D. in engineering and public policy and civil and environmental engineering from Carnegie Mellon and is a Leadership in Energy and Environmental Design (LEED) Accredited Professional in Building Design and Construction.

R. Rhoads Stephenson is currently a technology consultant. Previously, he held a number of positions at the Jet Propulsion Laboratory (JPL), the National Highway Traffic Safety Administration (NHTSA), and Martin Marietta Corporation. At JPL, the positions in which he served included deputy director and acting director, technology and applications programs; manager, electronics and control division; deputy manager, control and energy conversion division; and manager, systems analysis section. He also served as associate administrator for research and development at NHTSA, and while at Martin Marietta Corporation he worked on energy conversion devices for space power. He has been a consultant to the Motor Vehicle Fire Research Institute, has been providing peer reviews of automotive safety issues, and has recently published a number of papers on crash-induced fire safety issues with motor vehicles, including hydrogen-fueled vehicles. He recently (2010-2011) was acting associate director of the Joint Center for Artificial Photosynthesis at the California Institute of Technology. He has extensive expertise in vehicle safety analysis, advanced technology systems, energy conversion technologies, and energy and environmental analysis. He has a B.S., an M.S., and a Ph.D. in mechanical engineering from Carnegie Mellon University.

Kathleen C. Taylor (NAE) is retired director of the Materials and Processes Laboratory at General Motors Research and Development and Planning Center, located in Warren, Michigan. Dr. Taylor was simultaneously chief scientist for General Motors of Canada, Ltd., in Oshawa, Ontario. Earlier she was department head for physics and physical chemistry and department head for environmental sciences. Currently, Dr. Taylor serves on the Department of Energy Hydrogen Technology Advisory Committee and on the board of the National Inventors Hall of Fame. She was awarded the Garvan Medal from the American Chemical Society. She is a member of the National Academy of Engineering, the American Academy of Arts and Sciences, and the Indian National Academy of Engineering, and she is a fellow of SAE International and the American Association for the Advancement of Science. She was president of the Materials Research Society and chair of the board of directors of the Gordon Research Conferences. She has expertise in research and development management, fuel cells, batteries, catalysis, exhaust emission control, and automotive materials. She received an A.B. in chemistry from Douglass College and a Ph.D. in physical chemistry from Northwestern University.

Brijesh Vyas is a distinguished member of the technical staff at LGS Innovations, LLC. Previously he was a member of the Nanotechnology and Integrated Photonic Research Departments at Bell Labs, Murray Hill, New Jersey, where he was responsible for advanced materials and processes for microelectromechanical and photonic devices. He was also technical manager of the energy conversion technology group, responsible for research on advanced materials and technologies for energy storage systems. He has led efforts to develop various rechargeable batteries and related energy conversion technologies for a variety of telecommunications applications. He was formerly at the Brookhaven National Laboratory and has been a guest professor at the Technical University of Denmark in Copenhagen, investigating corrosion and erosion of metals. He received the Sam Tour Award from the American Society of Materials and Testing. His areas of expertise include materials science, electrochemistry, and corrosion. He served on the NRC Committee to Review the U.S. Advanced Battery Consortium's Electric Vehicle Battery R&D Project Selection Process. He received a bachelor's degree in metallurgical engineering from the Indian Institute of Technology in Bombay and a Ph.D. in materials science from the State University of New York, Stony Brook.

B

Recommendations from the National Research Council's *Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report*

CHAPTER 2: MAJOR CROSSCUTTING ISSUES

Safety

Recommendation [2-1]. The Partnership should establish a program to address all end-to-end safety aspects in addition to the existing codes and standards work. This work should be based on the pathways work and should include production, distribution, dispensing, and the vehicles. It should apply to all six alternative fuels and their associated vehicle types, including the use of high-voltage electricity on many of these vehicles. [NRC, 2010, p. 42.]

Recommendation [2-2]. The Partnership should generate and act on a failure modes and effects analysis of the full pressure vessel assembly, which includes the attached components and the human interface at the pump. Accelerated laboratory tests need to be run to identify failure/degradation modes of the pressure vessel and the mechanisms leading to failure. A nondestructive test program needs to be developed to assess pressure vessel integrity, which should serve both as a tool for quality control and as a means of checking for damage in service. The work on the analysis of worldwide natural gas and hydrogen incidents should continue. An R&D program should be established to develop a new generation of pressure-relief devices that can protect the storage tank from localized fire. [NRC, 2010, p. 42.]

Recommendation [2-3]. The hydrogen compatibility (including embrittlement) program should be continued. The Partnership should have experts in hydrogen embrittlement review the operating conditions and materials in the high-pressure delivery and refueling stations for potential problem areas, including welds and nonmetallic materials. [NRC, 2010, p. 42.]

Recommendation [2-4]. The Partnership should establish an emergency response R&D program with the involvement of emergency responders and research organizations to do fundamental work on the response to incidents involving alternative fuels. High-voltage batteries and electrical systems should also be included. [NRC, 2010, p. 42.]

Recommendation [2-5]. The Partnership should fully integrate the DOT safety efforts into the safety and the codes and standards aspects of the FreedomCAR and Fuel Partnership. All relevant parts of the DOT should be included: those involving passenger vehicles, trucks, the hydrogen bus program, pipelines and hazardous materials, fuel delivery trailers, and others. Alternative fuels should be included. The DOE and the Partnership's Executive Steering Group should consider adding a high-level DOT representative to the ESG. [NRC, 2010, pp. 42-43.]

Battery Electric and Plug-in Hybrid Electric Vehicles and the U.S. Electric Grid

Recommendation [2-6]. The grid interaction technical team should work with state utility regulatory authorities, perhaps through the National Association of Regulatory Utility Commissioners, to ensure that the incentives provided by state regulations mesh well with the national interest in vehicle deployment, reduced oil consumption, and lower greenhouse gas emissions. [NRC, 2010, p. 49.]

Recommendation [2-7]. The grid interaction technical team should continue to encourage and, where appropriate, facilitate the ongoing development of open-architecture standards for smart-vehicle/smart-grid interconnections currently being developed by the Institute of Electrical and Electronics Engineers and the Society of Automotive Engineers. In doing so, the technical team should encourage participation from the purveyors of smart-grid systems and battery suppliers as well as from the electric utility industry. [NRC, 2010, pp. 49-50.]

Recommendation [2-8]. Standards for the reuse of electric vehicle batteries should be developed under leadership of the grid interaction technical team, and training materials for the use of these standards should be developed in parallel. [NRC, 2010, p. 50.]

Persisting Trends in Automotive Innovation: Implications for the FreedomCAR and Fuel Partnership

Recommendation [2-9]. The Partnership should consider including manufacturing processes among the precompetitive R&D programs. Because its funding originates in the United States, the Partnership should emphasize the technologies and methods most capable of realizing advanced vehicle production in the United States, to the extent that this is feasible. [NRC, 2010, p. 51.]

Recommendation [2-10]. As the basic platform of the automobile becomes more modular, interface standards will be required to enable greater competition among technology alternatives. While specific interface standards have been discussed elsewhere in this report, the Partnership should also consider conducting a more general review of areas in which industry-wide standards could accelerate the pace of innovation and lower its cost. [NRC, 2010, p. 51.]

Recommendation [2-11]. The Partnership should seek out and implement methods to allow new, nontraditional suppliers—especially, emerging entrepreneurial companies—to participate in the innovation process. The Small Business Innovation Research (SBIR) program can become a highly productive source of innovation, and the Partnership should review its linkages with this program and strengthen them where appropriate. [NRC, 2010, p. 52.]

Environmental Impacts of Alternative Pathways

Recommendation [2-12]. The Partnership should undertake a review of the state of methods and case studies that have been carried out on environmental impacts related to the technologies under development. This review would answer some remaining open questions and help direct systems studies so as to maximize their efforts to characterize the environmental impacts of different fuel pathways. [NRC, 2010, p. 55.]

Recommendation [2-13]. The Partnership should strengthen the links between the systems analysis teams and the technical teams. In particular, technological goals and targets should include consideration of priorities established in systems analysis, and systems analysis should be conducted on emerging technologies identified by the technical teams. [NRC, 2010, p. 55.]

Recommendation [2-14]. The Partnership should consider incorporating the broader scope of a "cradle-to-grave" analysis rather than a "source (well)-to-wheels" approach in program planning from production to recycling in order to better consider total energy consumption, total emissions, and the total environmental impact of various energy/vehicle pathways and technologies. [NRC, 2010, p. 55.]

CHAPTER 3: VEHICLE SUBSYSTEMS

Advanced Combustion, Emissions Control, and Hydrocarbon Fuels

Recommendation [3-1]. The DOE should continue to support financially, be active in, and work to further enhance the collaborations among the national laboratories, industry, and academia in order most effectively to direct research efforts to areas where enhanced fundamental understanding is most needed to improve internal combustion engine and aftertreatment power-train performance. [NRC, 2010, p. 64.]

Recommendation [3-2]. The DOE should continue to support the development and dissemination of the open-source-code computational fluid dynamics program KIVA. This tool is critical to integrating the new understanding of combustion and emission processes into a framework that allows it to be used to guide further research and identify fuel and engine operating conditions that will maximize reductions in fuel consumption over the entire operating range of the engine. [NRC, 2010, p. 64.]

Recommendation [3-3]. The advanced combustion and emission control technical team should engage with the biofuels research community to ensure that the biofuels research which the team is conducting is consistent with and leverages the latest developments in the field of biofuels R&D. [NRC, 2010, p. 64.]

Recommendation [3-4]. As the vehicle mix within the on-the-road light-duty vehicle fleet is likely to change with the implementation of the new fuel economy standards, the advanced combustion and emission control technical team should interface with the system modeling technical team to make sure that their research programs are consistent with the changing demands for the optimal matching of the engine operational regimes, power management, and emission control that will be imposed on the internal combustion engine and hybrid power trains as the vehicle characteristics evolve. [NRC, 2010, pp. 64-65.]

Fuel Cells

Recommendation [3-5]. As the auto companies begin to down-select technologies for fuel cell vehicles, they must focus their limited R&D resources on development engineering for the platform selected and move into the competitive (as distinct from precompetitive) arena. The only way that alternative fuel cell systems and components can receive sufficient attention to mitigate the overall program risk is for the precompetitive program, sponsored largely by the DOE, to support them. Thus, the DOE should increase its focus on precompetitive R&D related to both the fuel cell stack and the balance of plant—the other components of the fuel cell system required for successful operation, such as controls, fuel storage, instrumentation, and so forth—to develop alternatives to the down-selected technologies. [NRC, 2010, p. 72.]

Recommendation [3-6]. The DOE should incorporate more of the advanced, most recent, nonproprietary OEM system configuration specifications in the various systems and cost models for fuel cell power plants. Systems configurations no longer demonstrated to be optimal should be abandoned in favor of best proven technology. [NRC, 2010, p. 72.]

Recommendation [3-7]. The DOE should establish backup technology paths, in particular for stack operation modes and stack components, with the fuel cell technical team to address the case of current technology selections determined not likely to meet the targets. The DOE should assess which critical technology development efforts are not yielding sufficient progress and ensure that adequate levels of support for alternative pathways are in place. [NRC, 2010, p. 72.]

Recommendation [3-8]. The DOE, with input from the fuel cell technical team, should evaluate, and in selected cases accelerate, the timing of the "go/no-go" decisions when it is evident that significant technological progress has been made and adopted by the OEMs. [NRC, 2010, p. 72.]

Onboard Hydrogen Storage

Recommendation [3-9]. The centers of excellence are well managed and have provided an excellent approach for organizing and managing a large, diverse research activity with many participants at various locations. Measures should be taken to continue research on the most promising approaches for onboard hydrogen storage materials. The complete documentation and communication of findings should be undertaken for all materials examined for the completed R&D. Furthermore, in view of the fact that the hydrogen storage program has been in place for less than a decade, the Partnership should strongly support continuing the funding of basic research activities. Public domain contractor reports should be available through links on the DOE EERE Web site. [NRC, 2010, pp. 83-84.]

Recommendation [3-10]. Research on compressed-gas storage should be expanded to include safety-related activities that determine cost and/or weight, such as validation of the design point for burst pressure ratio at beginning of life and end of life and evaluation of Type 3 versus Type 4 storage vessels. Furthermore, finite-element modeling of stresses and heat flow in fires, investigative work on wraps (i.e., translation efficiency), and analysis of applicability of compressed-gas storage to specific vehicle types would be beneficial. [NRC, 2010, p. 84.]

Recommendation [3-11]. The high cost of aerospace-quality carbon fiber is a major impediment to achieving cost-effective compressed-hydrogen storage. The reduction of fiber cost and the use of alternative fibers should be a major focus for the future. Systems analysis methodology should be applied to needed critical cost reductions. [NRC, 2010, p. 84.]

Recommendation [3-12]. The hydrogen storage program is one of the most critical parts of the hydrogen/fuel cell vehicle part of the FreedomCAR and Fuel Partnership—both for physical (compressed gas) and for materials storage. It should continue to be funded, especially the systems-level work in the Hydrogen Storage Engineering COE. Efforts should also be directed to compressed-gas storage to help achieve weight and cost reduction while maintaining safety. [NRC, 2010, p. 84.]

Recommendation [3-13]. The time for charging the hydrogen storage material with hydrogen (refueling time) is a program goal (3 minutes for a 5 kg charge). Concepts beyond materials properties alone should be explored to meet this challenge for customer satisfaction, and will require coordination with the areas of production, off-board storage, and dispensing. [NRC, 2010, p. 84.]

Recommendation [3-14]. There should be an effort to anticipate hydrogen storage material property and performance requirements that will place demands on developed systems—for example, purity and response to impurities, aging and lifetime prediction, and safety in adverse environments. Linkage between the hydrogen storage and production and delivery activities should receive attention. [NRC, 2010, p. 84.]

Recommendation [3-15]. The search for suitable onboard hydrogen storage materials has been broadly based, and significant progress is reported. Nonetheless the current materials are not close to the long-range goals of the Partnership. Onboard hydrogen storage R&D risks losing out to near-term applications for future emphasis and funding. The management of a long-term/short-term joint portfolio should be given consideration. [NRC, 2010, pp. 84-85.]

Electrochemical Energy Storage

Recommendation [3-16]. The Partnership should revisit and modify, as necessary, the goals and targets for battery electric vehicles in view of the changing market conditions and improvements in technologies. [NRC, 2010, p. 93.]

Recommendation [3-17]. The Partnership should significantly intensify its efforts to develop improved materials and systems for high-energy batteries for both plug-in electric vehicles and battery electric vehicles. [NRC, 2010, p. 93.]

Recommendation [3-18]. The Partnership should conduct a study to determine the cost of recycling batteries and the potential of savings from recycled materials. A research program on improved processes for recycling advanced batteries should be initiated in order to reduce the cost of the processes and recover useful materials and to reduce potentially hazardous toxic waste and, if necessary, to explore and develop new processes that preserve and recycle a much larger portion of the battery values. [NRC, 2010, p. 93.]

Electric Propulsion and Electrical Systems

Recommendation [3-19]. The Partnership should continue to focus on activities to reduce the cost, size, and losses in the power electronics and electrical machines. [NRC, 2010, p. 105.]

Recommendation [3-20]. The Partnership should conduct a project to evaluate the effect of battery charging on lithium-ion battery packs as a function of the cell chemistries, cell geometries, and configurations in the pack; battery string voltages; and numbers of parallel strings. A standardized method for these evaluations should be developed to ensure the safety of battery packs during vehicle operation as well as during plug-in charging. [NRC, 2010, p. 105.]

Recommendation [3-21]. The Partnership should consider conducting a project to investigate induction motors as replacements for the permanent magnet motors now almost universally used for electric propulsion. [NRC, 2010, p. 105.]

Structural Materials

Recommendation [3-22]. The materials technical team should develop a systems-analysis methodology to determine the currently most cost-effective way for achieving a 50 percent weight reduction for hybrid and fuel cell vehicles. The materials team needs to evaluate how the cost penalty changes as a function of the percent weight reduction, assuming that the most effective mix of materials is used at each step in the weight-reduction process. The analysis should be updated on a regular basis as the cost structures change as a result of process research breakthroughs and commercial developments. [NRC, 2010, p. 108.]

Recommendation [3-23]. The magnesium castings study is completed, and no further technical effort is anticipated by the Partnership as recommended in the Phase 2 report. However, magnesium castings should be considered in completing the cost reduction recommendation listed above. [NRC, 2010, p. 109.]

Recommendation [3-24]. Methods for the recycling of carbon-reinforced composites need to be developed. [NRC, 2010, p. 109.]

CHAPTER 4: HYDROGEN AND BIOFUELS

Hydrogen Fuel Pathways

Recommendation [4-1]. The DOE should broaden the role of the fuel pathways integration technical team (FPITT) to include an investigation of the pathways to provide energy for all three approaches currently included in the Partnership. This broader role could include not only the current technical subgroups for hydrogen, but also subgroups on biofuels utilization in advanced internal combustion engines and electricity generation requirements for PHEVs and BEVs, with appropriate industrial representation on each. The role of the parent FPITT would be to integrate the efforts of these subgroups and to provide an overall perspective of the issues associated with providing the required energy in a variety of scenarios that meet future personal transportation needs. [NRC, 2010, p. 118.]

Hydrogen Production

Hydrogen Production from Coal and Biomass

Recommendation [4-2]. The DOE's Fuel Cell Technologies program and the Office of Fossil Energy should continue to emphasize the importance of demonstrated CO_2 disposal in enabling essential pathways for hydrogen production, especially for coal. [NRC, 2010, pp. 120-121.]

Recommendation [4-3]. The Fuel Cell Technologies program should adjust its Technology Roadmap to account for the possibility that CO_2 sequestration will not enable a midterm readiness for commercial hydrogen production from coal. It should also consider the consequences to the program of apparent large increases in U.S. natural gas reserves. [NRC, 2010, p. 121.]

Recommendation [4-4]. The EERE should continue to work closely with the Office of Fossil Energy to vigorously pursue advanced chemical and biological concepts for carbon disposal as a hedge against the inability of geological storage to deliver a publicly acceptable and cost-effective solution in a timely manner. The committee also notes that some of the technologies now being investigated might offer benefits in the small-scale capture and sequestration of carbon from distributed sources. [NRC, 2010, p. 121.]

Recommendation [4-5]. The DOE should continue to evaluate the availability of biological feedstocks for hydrogen in light of the many other claims on this resource—liquid fuels, chemical feedstocks, electricity, food, and others. [NRC, 2010, p. 121.]

Reforming of Bio-Derived Fuels

Recommendation [4-6]. The Partnership should prioritize the many biomass-to-biofuel-to-hydrogen process pathways in order to bring further focus to development in this very broad area. [NRC, 2010, p. 123.]

High-Temperature Thermochemical Splitting of Water

Recommendation [4-7]. The Partnership should consider conducting a workshop to ensure that all potentially attractive high-temperature thermochemical cycles have been identified, and it should carry out a systems analysis of candidate systems to identify the most promising approaches, which can then be funded as money becomes available. [NRC, 2010, p. 123.]

Recommendation [4-8]. The EERE funding for high-temperature thermochemical cycle projects has varied widely and is very low in FY 2009. The committee believes that these centralized production techniques are important, and thus adequate and stable funding for them should be considered. [NRC, 2010, pp. 123-124.]

Electrolytic Processes

Recommendation [4-9]. Water electrolysis should remain an integral part of the future hydrogen infrastructure development. The DOE should continue to fund novel water electrolysis materials and methods, including alternative membranes, alternative catalysts, high-temperature and -pressure operation, advanced engineering concepts, and systems analysis. Additional efforts should be placed on advanced integration concepts in which the electrolyzer is co-engineered with subsequent upstream and downstream unit operations to improve the overall efficiency of a stand-alone system. [NRC, 2010, p. 126.]

Wind- and Solar-Driven Electrolysis

Recommendation [4-10]. Commercial demonstrations should be encouraged for new designs based on established electrolytic processes. For newer concepts such as high-temperature solid oxide systems, efforts should remain focused on laboratory evaluations of the potential for lifetime and durability, as well as on laboratory performance assessments. [NRC, 2010, p. 126.]

Recommendation [4-11]. Work on close coupling of wind and solar energy with electrolysis should be continued with stable funding. Further improvements in electrolyzers, including higher stack pressure, and in power electronics will benefit this application. [NRC, 2010, p. 126.]

Photolytic Processes

Recommendation [4-12]. The Partnership should examine the goals for the photolytic approach to producing hydrogen using microorganisms and formulate a vision with defined targets. Otherwise, this approach should be deemphasized as an active research area for hydrogen production. [NRC, 2010, p. 128.]

Hydrogen Delivery, Dispensing, and Transition Supply

Recommendation [4-13]. Hydrogen delivery, storage, and dispensing should be based on the program needed to achieve the cost goal for 2017. If it is not feasible to achieve that cost goal, emphasis should be placed on those areas that would most directly impact the 2015 decision regarding commercialization. In the view of the committee, pipeline, liquefaction, and compression programs are likely to have the greatest impact in the 2015 time frame. The cost target should be revised to be consistent with the program that is carried out. [NRC, 2010, p. 129.]

Biofuels for Internal Combustion Engines

Recommendation [4-14]. A thorough systems analysis of the complete biofuel distribution and end-use system should be done. This should include (1) an analysis of the fuel- and engine-efficiency gains possible through ICE technology development with likely particular biofuels or mixtures of biofuels and conventional petroleum fuels, and (2) a thorough analysis of the biofuel distribution system needed to deliver these possible fuels or mixtures to the end-use application. [NRC, 2010, p. 132.]

REFERENCE

NRC (National Research Council). 2010. *Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report.* Washington, D.C.: The National Academies Press.

C

Organizational Chart for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy

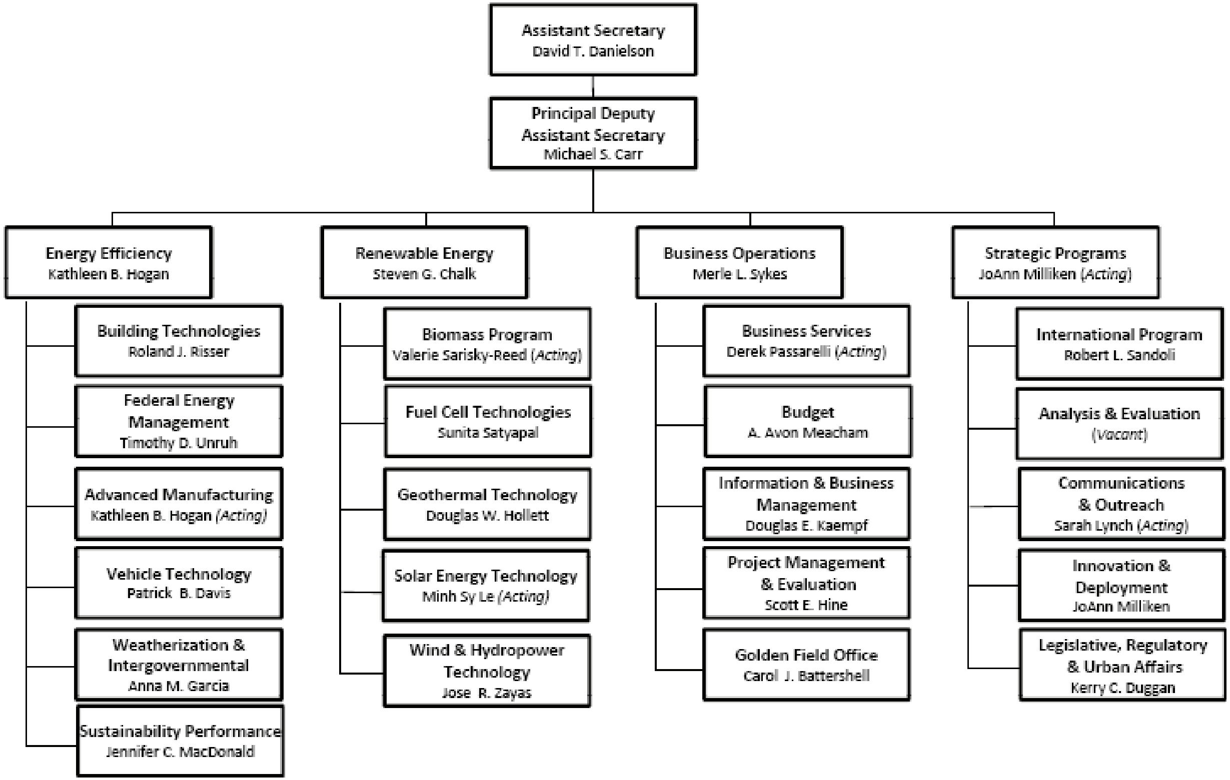

FIGURE C-1 Organizational chart for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Available at http://www1.eere.energy.gov/office_eere/pdfs/eere_orgchart.pdf, accessed November 24, 2012.

D

Committee Meetings and Presentations

COMMITTEE MEETING, WASHINGTON, D.C., DECEMBER 5-6, 2011

U.S. DRIVE Overview Presentation
Christy Cooper, U.S. Department of Energy (DOE) Director, U.S. DRIVE Partnership

Partnership Target Setting Process
Jake Ward, DOE Vehicle Technologies Program Analyst

DOE Perspective on U.S. DRIVE and Overview of the Vehicle Technologies Program
Patrick Davis, Vehicle Technologies Program Manager

Vehicle Operations Group Perspective on U.S. DRIVE
William Peirce, Vehicle Technologies Program Manager, General Motors

Utility Operations Group Perspective on U.S. DRIVE
Haukur Asgeirsson, Manager—Engineering, Distribution Operations, Power Systems Technology, DTE Energy
Richard Cromie, Program Manager, Electric Transportation, Southern California Edison

DOE Perspective on U.S. DRIVE and Overview of the Hydrogen and Fuel Cell Technologies Program
Sunita Satyapal, Hydrogen and Fuel Cell Technologies Program Manager

Fuels Operations Group Perspective on U.S. DRIVE
Puneet Verma, Biofuels and Hydrogen Unit, Chevron
Jack Jordan, Manager, Fuel Compliance and Trends, ConocoPhillips

Coal to Liquids
Sam Tam, Director, Division of Advanced Energy Systems, Office of Fossil Energy

Natural Gas as Transportation Energy Source:
Natural Gas as a Direct Transportation Fuel
Kevin Stork, Fuels Technology Team Lead, DOE Vehicle Technologies Program
Natural Gas as a Feedstock for Hydrogen
Fred Joseck, Technology Analyst, DOE Fuel Cell Technologies Program

Biomass and Biofuels
Valerie Reed, Conversion Team Lead, Biomass Program, Office of Energy Efficiency and Renewable Energy

Smart Grid and Renewable Electricity
Patricia Hoffman, Assistant Secretary for Electricity Delivery and Energy Reliability

COMMITTEE MEETING, WASHINGTON, D.C., JANUARY 26-27, 2012

Electrochemical Energy Storage Technical Team
Ronald Elder, Chrysler; David Howell, DOE

Electrical and Electronics Technical Team
John Czubay, General Motors; Susan Rogers, DOE

Advanced Combustion and Emissions Control Technical Team
Ken Howden, DOE; Richard Peterson, General Motors

Materials Technical Team
Carol Schutte, DOE; Matt Zaluzec, Ford

Vehicle System and Analysis Technical Team
Lee Slezak, DOE

Grid Interaction Technical Team
Keith Hardy, Argonne National Laboratory; Eric Lee, Chrysler

Fuel Cell Technical Team
Kathi Epping-Martin, DOE; Craig Gittleman, General Motors

Hydrogen Storage Technical Team
Scott Jorgensen, General Motors; Ned Stetson, DOE

Hydrogen Production Technical Team
Sara Dillich, DOE; Tecle Rufael, Chevron

Hydrogen Delivery Technical Team
James Simnick, BP; Scott Weil, Pacific Northwest National Laboratory

Fuel Pathway Integration Technical Team
Fred Joseck, DOE; Matt Watkins, ExxonMobil

Codes and Standards Technical Team
Antonio Ruiz, DOE; Ian Sutherland, General Motors

COMMITTEE MEETING, WASHINGTON, D.C., MARCH 12-13, 2012

Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electrocatalyst Degradation
Deborah Myers, Group Leader, Hydrogen and Fuel Cell Materials, Chemical Sciences and Engineering Division, Argonne National Laboratory

Hydrogen Storage Engineering Center of Excellence
Don Anton, Director, Hydrogen Storage Engineering Center of Excellence, Savannah River National Laboratory

Hydrogen Transportation in Germany—Status and Plans
Thorsten Herbert, Nationale Organisation Wasserstoff und Brennstoffzellentechnologie (by phone)

Hydrogen Transportation in Japan—Status and Plans
Robert Wimmer, National Manager, Energy and Environmental Research, Technical and Regulatory Affairs, Toyota North America, Inc.

Hydrogen Storage and Electrochemical/Battery Storage
John Vetrano, Program Manager, DOE Office of Science, Basic Energy Sciences

ARPA-E Activities in Electrochemical/Battery Storage
Dane Boysen, Program Director, Advanced Research Projects Agency-Energy (ARPA-E)

Summary of Committee Subgroup Discussion with General Motors
Glenn Eisman, Committee Member

Daimler Perspective on Hydrogen and Fuel Cells
William Craven, General Manager, Regulatory Affairs, Daimler AG

COMMITTEE MEETING, WASHINGTON, D.C., JUNE 4-5, 2012

Update on Battery Activity
David Howell, Team Lead for Hybrid Electric Systems, DOE Vehicle Technologies Program

Wireless Charging: Technology Status and Challenges
David Anderson, Vehicle Systems, Simulation, and Testing, DOE Vehicle Technologies Program

High Temperature Nuclear Reactors for Hydrogen Production
Carl Sink, DOE Office of Nuclear Energy

Summary of Site Visits to Lincoln Composites and Quantum Technologies
R. Rhoads Stephenson and Kathleen C. Taylor, Committee Members

Summary of Site Visits to GM-Torrance, AC Propulsion, and Southern California Edison
Linos Jacovides, R. Rhoads Stephenson, and Kathryn Bullock, Committee Members

Summary of Site Visit to GM-Fuel Cell Facility
Glenn Eisman, Dennis Corrigan, and Robert Nowak, Committee Members

Honda's Perspective on Fuel Cell, Electric, and Natural Gas Vehicles
Robert Bienenfeld, Sr., Manager, Environment and Energy Strategy, Honda Motor Co., Inc.

COMMITTEE SUBGROUP MEETINGS

Committee subgroups also made visits to General Motors, Honeoye Falls, New York; Lincoln Composites, Lincoln, Nebraska; Quantum Technologies, Irvine, California; USCAR Headquarters, Southfield, Michigan; General Motors Advanced Technology Center, Torrance, California; AC Propulsion, San Dimas, California; Southern California Edison, Westminster, California; and Structural Composites Industries (SCI), Pomona, California.

E

Acronyms and Abbreviations

ac	alternating current
ACEA	European Automobile Manufacturers' Association
ACEC	advanced combustion and emission control (technical team)
AEV	all-electric vehicle
ANL	Argonne National Laboratory
APEEM	Advanced Power and Electronic Motors
ARPA-E	Advanced Research Projects Agency-Energy (DOE)
ARRA	American Recovery and Reinvestment Act of 2009
B&EDT	batteries and electric drive technologies
BES	Basic Energy Sciences (Office of; DOE)
BEV	battery electric vehicle
BMEP	brake mean effective pressure
BNL	Brookhaven National Laboratory
BTE	brake thermal efficiency
CAFE	Corporate Average Fuel Economy
CAPEX	capital expenditure
CCS	carbon capture and sequestration
CFD	computational fluid dynamics
CLEERS	Crosscut Lean Exhaust Emission Reduction Simulation
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
COE	center of excellence

COF	covalent organic framework
CPU	central processing unit
CRADA	Cooperative Research and Development Agreement
CRC	Coordinating Research Council
dc	direct current
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRIVE	*D*riving *R*esearch and *I*nnovation for *V*ehicle Efficiency and *E*nergy Sustainability
E85	85 percent ethanol
ECN	Engine Combustion Network
EERE	Energy Efficiency and Renewable Energy (Office of; DOE)
EGR	exhaust gas recirculation
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EREV	extended-range electric vehicle
ESG	Executive Steering Group
EUMD	end-use measurement device
EV	electric vehicle
EVSE	electric vehicle supply equipment
FACE	Fuels for Advanced Combustion Engines
FCFP	FreedomCAR and Fuel Partnership
FCTP	Fuel Cell Technologies Program
FCV	fuel cell vehicle
FCVT	FreedomCAR and Vehicle Technologies (program)
FE	Fossil Energy (Office of; DOE)
FPITT	fuel pathway integration technical team
FY	fiscal year
gge	gallon gasoline equivalent
GHG	greenhouse gas
GITT	grid integration technical team
GM	General Motors
GPU	graphical processing unit
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (model)
GTR	Global Technical Regulation

H, H_2	hydrogen
H2A	Hydrogen Technology (model)
HC	hydrocarbon
HCCI	homogeneous charge compression ignition
HEV	hybrid electric vehicle
HFCTP	Hydrogen and Fuel Cell Technologies Program
HFCV	hydrogen fuel cell vehicle
HHV	higher heating value
HTML	high-temperature materials laboratory
ICE	internal combustion engine
IEEE	Institute of Electrical and Electronics Engineers
IP	intellectual property
ISO	International Organization for Standardization
JCAP	Joint Center for Artificial Photosynthesis
kg	kilogram
kHz	kilohertz
kW	kilowatt
kW_e	kilowatt (electric)
kWh	kilowatt-hour
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LDV	light-duty vehicle
Li-ion	lithium-ion
LLNL	Lawrence Livermore National Laboratory
LNG	liquefied natural gas
LTC	low-temperature combustion
MEA	membrane electrode assembly
Mg	magnesium
MOF	metal organic framework
MPa	megapascal
mpg	miles per gallon
MTT	materials technical team
MY	model year
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NE	Nuclear Energy (Office of; DOE)

NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NO_x	nitrogen oxides
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
OD&A	outreach, deployment and analysis
OEM	original equipment manufacturer
OPEX	operating expenditure
ORNL	Oak Ridge National Laboratory
PAN	polyacrylnitrile
PEC	photoelectrochemical
PEM	proton exchange membrane
PGM	platinum group metal
PHEV	plug-in hybrid electric vehicle
PM	particulate matter; permanent magnet
PNGV	Partnership for a New Generation of Vehicles
PNNL	Pacific Northwest National Laboratory
PSAT	Powertrain Systems Analysis Toolkit
psi	pounds per square inch
R&D	research and development
RCCI	reactivity controlled compression ignition
RCS	regulations, codes, and standards
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SBIR	Small Business Innovation Research
SC	Science (Office of; DOE)
SCR	selective catalytic reduction
SCS	Safety, Codes and Standards
SDO	standards development organization
SiC	silicon carbide
SIE	spark ignition engine
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
SS	solid state
ST	solar thermal
STTR	Small Business Technology Transfer
SUV	sport utility vehicle

T2B5	Tier 2 Bin 5 (standards)
21CTP	21st Century Truck Partnership
TRL	technology readiness level
USABC	United States Advanced Battery Consortium
USCAR	U.S. Council for Automotive Research
U.S. DRIVE	*D*riving *R*esearch and *I*nnovation for *V*ehicle Efficiency and *E*nergy Sustainability
VSATT	vehicle systems and analysis technical team
VSST	vehicle systems simulation and testing
VT	vehicle technologies
VTP	Vehicle Technologies Program (Office of)
ZEV	zero-emission vehicle