Linkages of DOE's Energy Storage R&D to Batteries and Ultracapacitors for Hybrid, Plug-In Hybrid, and Electric Vehicles

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Notice

Executive Summary

I. Study Overview

This study identifies and documents extensive connections (or linkages) between the U.S. Department of Energy's (DOE) applied research in energy storage for vehicles and downstream innovations in battery and ultracapacitor technologies for hybrid and electric vehicles. Linkages were found between DOE funding and the following innovations:

- Nickel metal hydride (NiMH) batteries – currently used in hybrid electric vehicles (HEVs);
- Lithium-ion (Li-ion) batteries – seen as the battery of choice for next-generation hybrid and electric vehicles; and
- Ultracapacitors – expected to provide a battery power boost for these vehicles.

In addition to direct linkages through U.S. battery suppliers, multiple indirect linkages were found — mainly through DOE-funded U.S. suppliers to Japanese suppliers of batteries for HEVs — suppliers who now have dominant world market share.

In comparison with other leading organizations, DOE ranks at or near the top in generating patents underpinning advanced battery and ultracapacitor technologies for hybrid and electric vehicles, exceeded only by the leading Japanese battery company Matsushita Electric/Panasonic. However, if companies funded by DOE through an industry consortium had consistently indicated government interest in all their affected patents, DOE may actually have ranked first. This study provides considerable evidence of DOE as an enabler of energy storage innovations for hybrid and electric vehicles over the past three decades.

II. Study Background, Purpose, Scope, Approach, and Limitations

For about three decades, DOE has supported research in advanced energy storage systems for vehicles with the goal of reducing reliance on the conventional internal combustion engine, emissions, and dependence on imported oil. Among a number of technical advancements needed to achieve these goals, advancements in energy storage have been widely recognized as extremely critical to achieving these goals.

The innovation of the HEV is a proven success in the U.S. market, with sales accelerating due to higher gasoline prices, rising public awareness of national environmental and energy issues, a wider supply of hybrid models, and increasing market acceptance. Meanwhile, the plug-in hybrid electric vehicle (PHEV) is gaining public attention as a practical means of further increasing miles per gallon of gasoline and of achieving larger reductions in U.S. dependency on imported oil for transportation. The current market emphasis is on hybridization; further technical developments and supporting infrastructure will likely be necessary to enable wide-spread use of the fully electric vehicle (EV).

The recent commercial progress in HEVs, PHEVs, and EVs provides demonstrated evidence that necessary advances in energy storage have been and are being made. These advances have centered on batteries and ultracapacitors. What role has DOE's research in energy storage played in these downstream advances in battery and ultracapacitor technologies for HEVs, PHEVs, and EVs? Have DOE research outputs found their way into these technologies, and to what extent?

This study sheds light on these questions by identifying and documenting connections between knowledge resulting from DOE's research and development (R&D) efforts in support of vehicle energy storage and downstream battery and ultracapacitor technologies for HEVs, PHEVs, and EVs.

The study's focus is solely on linkages to battery and ultracapacitor technologies for HEVs, PHEVs, and EVs, and not to other types of applications for these technologies that may have emerged. Furthermore, the focus is on batteries and ultracapacitors and not on other technologies developed in support of HEVs, PHEVs, and EVs.

To trace these connections, the study uses an historical tracing method, supported by the techniques of interview, inquiry into licensing agreements, assessment of institutional roles and relationships, and document review, in combination with patent citation analysis. These are complementary methods, which in combination provide a more comprehensive analysis of linkages between research knowledge outputs and the downstream applications of that knowledge than would either of these methods used alone.

- Interviews with experts help to avoid missing important avenues of knowledge creation and dissemination that do not necessarily show up in a patent citation analysis.

- Document reviews help to substantiate relevant events and assess their importance, and verify dates and specifics that may have faded from the memories of experts.

- Patent citation analysis has strength of objectivity in identifying the creation of intellectual property from R&D and identifying those who are users of that knowledge insofar as they are citing the resulting patents. Patent citation analysis has been used extensively in the analysis of technological innovation because knowledge with potential commercial application is often patented.

- Investigation of licensing agreements is useful in demonstrating impacts that may not show up in patent citation analysis.

Because the downstream application area of interest — battery and ultracapacitor technologies for HEVs/PHEVs/EVs — is pre-selected, and the search is for linkages from that application area back to DOE's energy storage research, the study is predominantly a "backward tracing" study. However, it also has elements of "forward tracing," particularly in the interview section and in the discussion of roles and responsibilities.

Despite the use of the multiple methods noted above, limitations remain that likely have resulted in an understatement of the linkages from DOE's research to applications in battery and ultracapacitor technologies for HEVs, PHEVs, and EVs. The limitations are detailed in the report.

[For more on study background, purpose, scope, approach, and limitations see Chapters 1 & 2.]

III. A Growing Market for HEVs and Growing Interest in PHEVs and EVs

Although HEVs account for only about 1 percent of total world new car production, sales are growing rapidly, at an average annual rate of more than 80 percent in the United States from 1999 to 2005, accelerating to a rate of nearly 140 percent in 2006. The world hybrid vehicle market in 2006 was estimated at 384,000 vehicles, two-thirds of which consisted of sales in the United States. Consumer interest in HEVs has been stimulated by rising fuel prices, as well as by the availability of an increasing number of HEV models and body styles aimed at a broad range of buyers. Some key market highlights follow:

- Because HEVs are already commercialized, they are of particular interest in the study. The world HEV battery market was estimated at $600 million in 2006, and has been projected to grow to $1.4 billion by 2010. Toyota had a 78 percent share of the world HEV market in 2006, followed by market shares of Honda, Ford, and General Motors.

- The PHEV is gaining in public awareness and attention. It offers greater potential for reductions in imported fuel and emissions than the HEV while still realizing the advantages offered by hybridization.

- The second generation of fully electric cars is still in the developmental and prototype stage. The EV, in contrast to the HEV and PHEV, uses no backup engine. Like the PHEV, the EV is recharged by plugging into the electric power grid. Broad use of the EV challenges both existing battery capacity and the nation's infrastructure for recharging away from home.

[For more on market developments see Chapter 3, Section 3.2]

IV. Advances in Technologies for HEVs, PHEVs, and EVs

With the involvement of DOE and multiple organizations, considerable gains have been made in battery and ultracapacitor technology from the beginning of the period examined (1976), when lead-acid battery technology was state-of-the-art, through the end of the study (2007), when NiMH batteries are routinely used in HEVs, and Li-ion are emerging for use in advanced HEVs and PHEVs in the relatively near term.

- The NiMH battery used in today's HEVs has been called battle-tested and safe, and is a proven and reliable power source for HEVs.

- The baseline costs of both NiMH and Li-ion batteries have been reduced, longevity is approaching the 15-year target, size and weight have been decreased, and power and energy performance have been improved.

- The use of DOE-developed test protocols for benchmarking batteries for HEVs, PHEVs, and EVs from suppliers the world over has become enabled, feasible, and common practice.

- Panasonic EV Energy, a joint venture between Toyota Motor Company and Panasonic Batteries (a subsidiary of Matsushita Electric), currently has more than 75 percent of the world NIMH HEV battery market.

- The Li-ion battery is widely seen as the battery of choice for next-generation HEVs and for PHEVs and EVs. It offers advantages of higher power and energy per unit weight and volume as compared with NiMH batteries. It has a better charge efficiency than NiMH batteries, and it also offers a potential for a longer life, a quicker charge, and perhaps, in the future, even lower costs. However, the Li-ion battery's reliability and safety does not yet meet targeted performance requirements.

- An ultracapacitor can release energy in quick bursts with more power than a battery, though it stores much less energy than a battery. It offers potential opportunities in energy storage by providing high peak power for hybrids when needed, extending battery life and reducing battery maintenance and replacement costs, and enabling battery downsizing. But it is still a technology under development.

[For more on energy storage technologies see Chapter 3, Sections 3.3-3.5.]

The focus of this study on advances in battery and ultracapacitor technologies for HEVs, PHEVs, and EVs does not diminish the contributions of DOE's other research efforts that are also furthering advances in hybrid and electric vehicles.

[For more on technology advances important to hybrid and electric vehicles see Chapter 3, Section 3.6.]

V. Findings On Involvement by Multiple Organizations

The study found a history of different organizations playing interconnected roles in battery and ultracapacitor R&D, and in their commercial applications. Some key findings are:

- In 1976, Congress charged a DOE predecessor, the Energy Research and Development Administration (ERDA), with accelerating research into EV and HEV technologies by passing the Electric and Hybrid Vehicle Research, Development, and Demonstration Act. This Act established the foundation for DOE's electric and hybrid vehicle R&D activities, when DOE was formed in 1977. Subsequent related legislation and policy actions over the years have provided additional direction to DOE's efforts in the field. The Vehicle Technologies (VT) Program of DOE's Energy Efficiency and Renewable Energy Office

(EERE) has provided focus and funding for U.S. energy storage research aimed at vehicles. The VT Program works in close partnership with the automotive industry to set goals for technology development.

- Government/industry partnerships have brought the combined R&D capabilities and resources of DOE, the national laboratories, and universities together with the know-how of auto manufacturers and suppliers in initiatives to improve fuel efficiency and decrease emissions of automobiles. Two sequential partnership programs are:
  - Partnership for a New Generation of Vehicles (PNGV), lasting from 1993–2001, and
  - FreedomCAR & Fuel Partnership (FreedomCAR), lasting from 2002–Present.

- Industry-led consortia have provided a funding conduit through which DOE has funded company R&D in vehicle energy storage, including:
  - U.S. Advanced Battery Consortium (USABC), formed in 1991 to develop electrochemical energy storage technologies that support commercialization of fuel cell, hybrid, and electric vehicles; and
  - U.S. Council for Automotive Research (USCAR), formed in 1992 to strengthen the broader technology base of the U.S. auto industry.

- DOE national laboratories, particularly the following, have contributed research results and testing: Argonne National Laboratory (ANL); Lawrence Berkeley National Laboratory (LBL); Idaho National Laboratory (INL); Brookhaven National Laboratory (BNL); Sandia National Laboratories (SNL); and National Renewable Energy Laboratory (NREL).

- Universities have contributed research results, funded primarily by the national laboratories.

- Automotive manufacturers and battery suppliers, and joint ventures among them have participated in R&D and commercialized batteries and ultracapacitors for HEVs/PHEVs/EVs.

- Foreign competitors and research institutes have contributed to R&D and made major advancements in commercialization. Other organizations, including societies, institutes, and advisory panels, have provided past critiques of DOE's research in the field.

[For more on organizational roles, see Chapter 4 & Appendix B.]

VI. Principal Findings on Linkages to Innovations

The study's findings provide evidence that DOE has played a significant role as an enabler of downstream innovation in battery and ultracapacitor technologies for HEVs, PHEVs, and EVs. Substantial linkages were found between DOE funding and NiMH batteries, used in today's HEVs. Extensive linkages were found between DOE funding and Li-ion batteries, seen as the next-generation battery for HEVs, PHEVs, and EVs. Extensive linkages were also found between DOE funding and ultracapacitors, which may be used in future HEVs, PHEVs, and EVs.

The study concludes that DOE has played a significant role in helping to form the foundation for commercial battery and ultracapacitor technologies for EVs, HEVs, and PHEVs.

Evidence found by interview, document review and licensing review

Interviewed DOE program staff emphasized connections between DOE funding of company research through the USABC, and advances in battery and ultracapacitor technologies for HEVs, PHEVs, and EVs. Document review supported the importance of these connections. Linkages through the Energy Conversion Devices (ECD) Ovonics group; Johnson Controls, Société des Accumulateurs Fixes et de Traction (SAFT), and their joint venture; and A123Systems appeared to be particularly important. Table ES-1 summarizes linkages through companies that were emphasized by experts.

Table ES- 1 Summary of Expert-Identified Major Linkages to Innovations of DOE Funding of Companies through the U.S. Advanced Battery Consortium (USABC)

Companies and Company Alliances Funded by DOE through USABC	Linkages to HEVs, PHEVs, and EVs
Company grouping of Energy Conversion Devices (ECD), Ovonic Battery Company, and Cobasys (referred to as ECD Ovonics in the report text and subsequent tables)	▪ Developed NiMH battery for EVs (used in GM's EV-1 all-electric car) ▪ Developed NiMH battery for HEVs ▪ Licensed its NiMH battery technology to all major battery manufacturers ▪ Pays royalties to DOE on its licensing fees ▪ Charged Panasonic & Toyota with patent infringement resulting in payments to ECD Ovonics and a cross-licensing and cooperative development settlement agreement ▪ Supplies its NiMHax® battery system for GM's 2007 Saturn Aura Green Line Hybrid Sedan and VUE Green Line SUV ▪ In partnership with A123Systems, is one of two battery supplier teams competing to supply Li-ion batteries for GM's Saturn VUE Green Line Plug-in Hybrid SUV
SAFT	▪ Supplied batteries for Daimler Chrysler's and GM's demonstration fleets of EVs in 1990s ▪ Supplies its STM Ni-Cd batteries to EVs in Europe ▪ Supplies its STH Ni-Cd batteries for HEVs
Johnson Controls-SAFT JV	▪ One of two battery supplier teams competing to supply Li-ion batteries for GM's Saturn VUE Green Line Plug-in Hybrid SUV
A123Systems	▪ In partnership with Cobasys is one of two battery supplier teams competing to supply Li-ion batteries for GM's Saturn VUE Green Line Plug-in Hybrid SUV

Note: Companies that are shown grouped together are affiliated or allied in battery development programs.

Highlights of evidence found by interview, document review and licensing review follow:

- General Motors and Daimler Chrysler powered their all-electric demonstration fleets in the early 1990s with DOE-funded NiMH batteries.

- NiMH batteries with higher power and extended cycle life were successfully demonstrated with DOE funding for use in HEVs, and subsequently auto makers used the batteries to demonstrate hybrid electric vehicles.

- Major battery suppliers around the world, including major Japanese battery suppliers, licensed ECD Ovonics' DOE-funded NiMH battery technology.

- Evidence was found of multiple indirect linkages from the major Japanese supplier of NiMH battery for HEVs (Matsushita Electric and its subsidiary Panasonic Battery) to DOE-funding. These indirect linkages occurred through licensing of ECD Ovonics NiMH technology, through citing by these Japanese companies of the resulting patents, and through the filing and resolution of a patent infringement case brought by ECD Ovonics against Matsushita Electric, Panasonic, and Toyota for infringing its NiMH battery technology.

- Royalty payments to DOE that have arisen from the licensing and incorporation of ECD Ovonics' technology in a NiMH battery provided by Sanyo for the Ford Hybrid Escape and the Honda Accord Hybrid demonstrate linkage of DOE-funded battery technology to HEVs.

- General Motors included NiMH batteries from Cobasys, part of the DOE-funded ECD Ovonics group, in its Saturn Aura Green Line Hybrid and Saturn VUE Green Line Hybrid.

- A national laboratory (ANL) recently licensed its advanced rechargeable lithium battery technologies to NanoeXa to develop and transfer into commercial use for next-generation HEV and PHEV applications.

- Battery test protocols developed by DOE national laboratories became the basis for automotive industry standards.

- General Motors has issued contracts to two partnerships of DOE-funded companies (a joint venture of Johnson Controls and SAFT and a partnership between A123Systems and Cobasys) for the supply of batteries for its prototype Saturn VUE Green Line Plug-in Hybrid.

- The national laboratories and the universities funded by the national laboratories have contributed to an extensive body of scientific and engineering knowledge in the field of vehicle energy storage technologies from which downstream researchers have drawn.

Evidence from broad patent citation analysis

A broad patent-citation analysis found that DOE-funded patents, conservatively counted, represented the second largest portfolio of HEV/PHEV/EV battery/ultracapacitor patents, next to the portfolio of Matsushita Electric/Panasonic Battery — itself with indirect linkages back to DOE-funded battery research. If additional patents of ECD Ovonics can appropriately be added to the DOE-funded set, DOE would likely have the largest portfolio of HEV/PHEV/EV battery/ultracapacitor patents. However, in order to provide a conservative estimate, ECD Ovonics patents were separately listed except for three patents that were specifically included in the DOE patent database.

- The study identified 71 DOE-funded patents.

- The number of DOE-funded battery and ultracapacitor patents cited by HEV/PHEV/EV patents was comparatively large (222), second only to the number of cited Matsushita Electric patents. DOE patents were cited 482 times. The large number of cited DOE patents, along with their relatively low average citation rate (2.17), suggests that DOE funding has formed a broad foundation for HEV/PHEV/EV battery/ultracapacitor technologies.

- There are a number of highly cited HEV/PHEV/EV battery/ultracapacitor patents that themselves cite previous DOE-funded battery and ultracapacitor patents. These findings are consistent with DOE's role in developing foundational technologies for the vehicle energy storage industry on which specific commercial innovations have been built.

- Overall, approximately 20 percent of HEV/PHEV/EV battery/ultracapacitor patents issued since 1994 cite at least one DOE-funded patent. Patents citing one or more DOE-funded patents include those of many leading organizations in HEV/PHEV/EV battery/ultracapacitor technology. In comparison, only one organization has more of its patents cited by other HEV/PHEV/EV battery/ultracapacitor patents than DOE: Matsushita Electric, with 26 percent. For further comparison, 15 percent of these patents cite Motorola's patents; 11 percent cite Sanyo's; 10 percent cite NEC's; 5 percent cite Honda's; and 3 percent cite Toyota's.

- There are 30 organizations other than DOE having more than 10 patents in the total HEV/PHEV/EV battery/ultracapacitor patent set. All 30 of these organizations have one or more HEV/PHEV/EV battery/ultracapacitor patents that cite a DOE patent.

- The patents of the different organizations funded by DOE were found to be citing each other extensively. This pattern of citations suggests that the inventions of the different groups funded by DOE are influencing each other. As a result, it appears that DOE funding not only has a direct impact on the group receiving funding, but also an indirect impact on other DOE-funded groups working in a similar area — a synergistic effect and a positive finding.

[For more on the linkages found through interview, document review, and analysis of downstream citing of a DOE-funded ECD Ovonics patent see Chapter 5; for more on linkages found through broad patent citation analysis see Chapter 6.]

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Chapter 1. Introduction

1.1 Background and Context: Public Support to Research on Vehicle Energy Storage Technologies

Over the past three decades, DOE has operated research programs directed toward technological advances in energy storage for vehicles. Although the energy storage programs have experienced change in the face of changing conditions and changing policy responses — including fluctuating energy demand and supply conditions, changing levels of funding, changes in program offices and names, and shifts in focus — DOE's research efforts in vehicle energy storage have continued. Currently, DOE's research programs to promote technologies for hybrid and electric vehicles are under the direction of the Vehicles Technologies (VT) Program, located within the EERE.

When DOE was created in 1976 from a variety of federal energy functions, among its many responsibilities was an early directive to administer an R&D program to advance development of technologies for hybrid and electric vehicles. The directive called for reducing both their energy requirements and their output of emissions. These actions leading to public support of R&D to increase energy efficiencies, including improvements in vehicle energy efficiency, followed the series of oil shocks in the 1970s that heightened public awareness of the growing dependence of the United States on imported oil.

Despite a second oil shock in 1979 in response to the Iranian Revolution, and the temporary reappearance of long lines at gas stations, oil supplies increased and fuel prices declined during the 1980s. Political attention to concerns about energy efficiency diminished. Public R&D efforts to increase energy conservation, and specifically DOE's vehicle efficiency R&D, were reduced, though not suspended. Then, early in the 1990s, steps were taken by both industry and government to re-intensify efforts to bring about more efficient vehicles.

Today, concerns about potential instability in world oil markets, higher gasoline prices, and concerns about emissions and climate change are again raising public attention to the need for advanced alternatives for powering vehicles. In 2005, transportation accounted for nearly 70 percent of petroleum consumed in the United States, of which 64 percent was motor gasoline.[1] Increasing the use of hybrid electric and electric vehicles offers one way to alleviate national problems associated with prime reliance on the internal combustion engine fueled by imported petroleum. However, technical challenges, particularly with respect to energy storage, have continued to impede their use.

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[1] U.S. Department of Energy, Energy Information Administration, Energy Statistics from Table F9a, "Total Petroleum Consumption Estimates by Sectors," 2005 (www.eia.doe.gov/emeu/states/sep_fuel/html/fuel_use_pa.html); and Table 3.13c Petroleum Consumption: Transportation and Electric Power Sectors (www.eia.doe.gov/mer/pdf/pages/sec3_33.pdf.

1.2 Need for Evaluation and Study Purpose

Considerable gains have been made in energy storage systems — particularly battery and ultracapacitor technologies — from the beginning of the period examined (1976), when lead-acid battery technology was state-of-the-art, to the present (2007), when NiMH batteries are routinely used in HEVs, and Li-ion batteries are emerging for volume-use in next-generation HEVs and PHEVs in the near term. There is no doubt that change has happened, but what role has DOE played in these advances?

Like other government programs, the VT Program is charged by Congress and the Executive Branch to demonstrate its effectiveness in meeting its objectives. In addition, good management practices include evaluation. EERE's PBA is responsible for assisting EERE programs with program evaluation activities, and it directed this study in collaboration with the VT Program.

Typical of applied research programs, the principal direct program output of the VT programs is knowledge generation. Program impact occurs when the new knowledge is taken up by others and used for benefit. However, the paths through which knowledge dissemination occurs tend to be complex, non-linear, not obvious, and often developing over a number of years. Tracing the flow of a research program's knowledge outputs to see where they go is among the methods of evaluation that are appropriate for a research program.

The purpose of this study is to conduct a knowledge tracing study, with an emphasis on identifying and documenting linkages from battery and ultracapacitor technologies for hybrid and electric vehicles back to support by DOE of advanced energy storage research for vehicles. Documenting these linkages will help answer questions about the real-world relevance of DOE's past research to downstream innovations of growing importance. It will provide evidence about VT Program's demonstrated progress toward meeting its mission to advance hybrid and electric vehicles.

1.3 Organization

An Executive Summary provides a study overview. The body of the report is presented in six main chapters, followed by a seventh chapter that summarizes conclusions.

Chapter 1 introduces the report. Chapter 2 discusses the study's evaluation methodology, as well as study limitations.

Chapter 3 provides technical and market overviews of the technologies addressed in the study: HEVs, PHEVs, and EVs, and NiMH and Li-ion batteries and ultracapacitors. The chapter conveys in lay terms a sense of the state of energy storage technologies at the beginning of the period of study and now. Briefly, it also discusses non-energy-storage technologies under development in support of HEVs, PHEVs, and EVs.

Chapter 4 provides an institutional analysis, an important step in conducting an historical tracing study. It discusses the roles of DOE/EERE, government/industry partnerships, industry consortia, national laboratories, universities funded by the national laboratories, and automotive manufacturers and battery suppliers.

The heart of the report, centered in Chapters 5 and 6, presents results. Chapter 5 presents the linkages identified by expert and document review, supplemented by selected forward patent tree analysis. Chapter 6 presents the results of a broader, backward patent citation analysis which documents linkages between patents describing battery and ultracapacitor technology for hybrid and electric vehicles and patents resulting from DOE-funded research. The findings show the extent of DOE's ties to HEV/PHEV/EV battery and ultracapacitor technologies through patents, relative to the ties of other leading organizations.

Five Appendices provide supplementary material. Appendix A extends Chapter 2 by providing methodological details on how the interviews were conducted and how the databases for the patent citation were developed. Appendix B supplements the institutional analysis of Chapter 4. Appendix C provides information supplementary to Chapter 5. Appendix D provides supplementary information for the broader patent citation analysis of Chapter 6.

Chapter 2. Study Methods

2.1 An Overview of Methods Used in the Study: Historical Tracing Supported by Patent Citation Analysis

To identify and document linkages between DOE R&D and downstream innovations, this study used the historical tracing method in combination with citation analysis.[2] The traditional tools of historical tracing and expert opinion solicited by interview and supported by document review were used. In addition, the study included an inquiry into licensing agreements and an assessment of institutional roles and relationships.

2.1.1 Historical Tracing

The historical tracing method investigates a series of interrelated events, taking either a forward or backward look. Going forward means starting with the research program of interest and tracing along the various paths from the R&D to downstream outcomes. Working backward means starting with a specific outcome of interest and tracing back to see whether the path backward leads to the targeted research program.

Because this study selects in advance the downstream outcome of interest — batteries and ultracapacitors in HEVs, PHEVs, and EVs — and excludes spillover effects, it takes primarily a backward-tracing approach, starting with the targeted outcome. However, there are also forward-tracing elements present in the study. Where forward knowledge flows were identified by experts, the study looked to see if there was supporting evidence either in terms of license agreements, news releases, or other relevant documents or citation linkages.

Integral to conducting an historical tracing study is providing sufficient context and background for understanding how and why linkages might exist and their likely consequences. This includes establishing the institutional context of relevant roles and relationships through which linkages occur. It includes providing adequate technical background for understanding the logic of connections among subject technologies and the ties between upstream R&D and downstream innovations. Finally, it includes anchoring to market conditions to help assess subjectively and qualitatively the economic importance of identified linkages. Thus, it is broader than citation analysis alone.

2.1.2 Citation Analysis

Citation analysis is one of several bibliometric methods used to show that intellectual property created by one party is being used — or at least referenced — by others. The several bibliometric methods, which also include paper and patent counts, data mining, and specialized analysis of citation intensity (e.g., hotspot analysis), are particularly relevant to

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[2] Historical tracing is one of multiple evaluation methods that are used to evaluate R&D programs. A directory of evaluation methods is provided by Rosalie Ruegg and Gretchen Jordan, *Overview of Evaluation Methods for R&D Programs; A Directory of Evaluation Methods Relevant to EERE Technology Development Programs*, March 2007. The Directory is available on line at www.eere.energy.gov/ba/pba/km_portal/docs/pdf/2007/RandBooklet.pdf.

R&D evaluation because knowledge and intellectual property are principal outputs of R&D programs. Citation analysis may include citations of publications by other publications, citations of patents by other patents, citations of publication by patents, and/or citations of patents by publications. However, the emphasis in this study is on patents cited by other patents.

The patent citation analysis presented in the report centers on citations between generations of patents. In the U.S. patent system, it is the duty of patent applicants to reference (or cite) all prior art of which they are aware that may affect the patentability of their invention. "Prior art" in a patent law system refers to all information that previously has been made available publicly such that it might affect a patent's claim of originality and, hence, its validity. Prior art may be in the form of previous patents, or published items such as scientific papers, technical disclosures, and trade magazines. In addition, patent examiners may reference prior art that limits the claims of the patent for which an application is being filed.

Patent citation analysis has been used extensively in the analysis of technological developments. In this type of analysis, a reference from a patent to a previous patent is regarded as recognition that some aspect of the earlier patent has had an impact on the development of the later patent. In the analysis presented in this report, patent citations are used to trace the role of DOE funding in the development of HEV/PHEV/EV battery and ultracapacitor technologies. Specifically, we identify DOE-funded patents that are in the group of HEV/PHEV/EV battery and ultracapacitor patents. We also identify DOE-funded patents that have been cited by those in the group of HEV/PHEV/EV battery and ultracapacitor patents. The idea behind the citation analysis is that the citing technologies have built in some way on the DOE-funded patents.

Patent citation analysis also has been employed in studies to evaluate the impact of particular patents on technological developments. This is based on the idea that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance. As such, they form the basis for many new innovations, and so are cited frequently by later patents. While it is not true to say that every highly cited patent is important, or that every infrequently cited patent is unimportant, research studies have shown a correlation between the rate of citations of a patent and its technological importance.

In the analysis in this report, therefore, we also use patent citations to evaluate the impact of particular patents in the development of HEV battery and ultracapacitor technologies. We highlight DOE-funded patents that have been cited frequently by HEV/PHEV/EV battery and ultracapacitor patents. We also highlight relevant individual patents and organizations that have built extensively on DOE-funded patents.

2.1.3 Planning for Expert Interview and Document Review

Expert interview was intended to provide a broad context for the study and an historical perspective on DOE's R&D program in energy storage, as well as to identify: (1) what "insiders" considered DOE's most noteworthy contributions to energy storage R&D, (2) the role of DOE in fostering industry's advancement toward successful commercialization of HEVs, PHEVs, and EVs, (3) specific linkages between DOE-supported R&D in energy storage technologies and batteries and ultracapacitors for HEVs, PHEVs, and EVs that might not be revealed by the patent citation analysis alone.

DOE/EERE research managers (one retired) were identified with the assistance of DOE's director of the study, Jeff Dowd, as having both a broad and in-depth knowledge of DOE's energy storage research. Following preliminary desk analysis, interviews were scheduled with four available research managers. As part of the interview, these research managers were asked to identify national laboratory research managers who would have similar knowledge at the national laboratory level. Those identified were contacted, and responses led to a focus on Argonne National Laboratory (ANL) and Lawrence Berkeley National Laboratory (LBL) and in-depth interviews with research managers in those laboratories. These six interviewees and their affiliations are listed at the end of the References.

Interviews were conducted using an interview guide with open-ended questions. The interview guide is reproduced in Appendix A. Because it was the intention of the interviewer to cast a wide net, the interview guide was used to ensure that the topics listed were covered during the discussion, but was not used to limit the scope of the discussions; interviewees were allowed free-rein in the discussion.

Early in the document review process, it was found that many of the industry managers involved in company research and commercialization of energy storage systems for HEVs, PHEVs, and EVs — and initially slated for interview — had been interviewed for related press releases and news articles, such that much of the desired information was available through this unobtrusive source. Hence, the decision was made to use these existing materials in lieu of conducting additional interviews with industry representatives.

2.1.4 Preparing for the Patent Citation Analysis

Identifying Patents for Analysis

The basic idea behind the patent citation analysis is to determine the linkages from DOE-funded patents to patents for HEV/PHEV/EV batteries and ultracapacitors. In order to carry out such an analysis, two patent sets must be defined — the population of DOE-funded patents, and the population of HEV/PHEV/EV battery/ultracapacitor patents. Neither of these patent sets is straightforward to construct, and our approach to defining each set is described as follows in steps A and B.

Step A. <u>Identifying DOE-Funded Patents</u>: Identifying patents funded by government agencies is often more difficult than identifying patents funded by companies. When a company funds internal research, any patented inventions emerging from this research will generally be assigned to the company itself. In order to construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries and acquisitions. On the other hand, a government agency may fund research in a variety of organizations. For example, as explained in Chapter 4 and Appendix B, DOE has funded energy storage research in a number of its national laboratories. Patents emerging from these laboratories may be assigned to DOE, but the patents may also be assigned to the organization that manages the laboratory or research center. For example, patents from SNL may be assigned to Lockheed Martin, while LNL patents may be assigned to the University of California, and ANL patents, to the University of Chicago. A further complication is that

DOE not only funds research in its own laboratories and research centers, but also funds research carried out by private companies. For example, much of the DOE funding for energy storage by companies was channeled through an industry consortium. If this research results in patented inventions, these patents are likely to be assigned to the company carrying out the research, rather than to DOE or the USABC, and the study found that the government interest may not even be identified in the patent — in fact, typically it was not. As explained in Chapter 5, the addition of expert interview to the study methods helped to identify some of the linkages that likely would have been missed altogether, or understated in terms of importance, by the citation analysis method alone.

In order to identify the population of DOE-funded patents, we used the following three different sources:

1. ***Office of Scientific and Technical Information (OSTI) Database*** – the first source we used was a database provided to us near the beginning of the study by DOE's OSTI for use in DOE-related projects such as this. This database was an invaluable resource in this project, in that it contains information on research grants provided by DOE since its inception. It also links these grants to the organizations or DOE centers carrying out the research, the sponsoring organization within DOE, and the patents that resulted from these DOE grants. For this project, we identified all patent records in the OSTI database that had a DOE contract number, were carried out by a DOE research center, or had a DOE sponsor. We then identified patent numbers associated with these records.

2. ***Patents Assigned to DOE*** – we identified a number of patents assigned to DOE that were not in the OSTI database. These either became available after the OSTI database was last updated or else had been omitted for some other reason. These additional patents were found by searching the U.S. patent database for patents assigned to DOE, using variations of the name,[3] and checking them against the existing database. Any patents not already in the OSTI database were added to the list of DOE patents.

3. ***Patents with DOE Government Interest*** – a patent has on its front page a section entitled "Government Interest", which details the rights that the government has in a particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research.

   We identified all patents that refer to "Department of Energy" or "DOE" in their Government Interest field, along with patents that refer to government contracts beginning with DE- or ENG-, since these abbreviations also denote DOE grants. Patents in this set that were not already in the OSTI database, and were not among

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[3] The search was not extended to companies that manage the DOE laboratories. It is not valid, for example, to include all Lockheed Martin patents since most are not from the DOE laboratories. Thus, the only Lockheed Martin patents (or those of other DOE laboratory operators) that are included are those that show up either in the OSTI database or through the search of patents that identify DOE in their field of interest (i.e., source 3).

those in the second group identified as assigned to DOE, were added to our list of DOE patents.

As a result of this process, we identified a total of 15,682 U.S. patents that are linked to DOE-funded research. We refer in the study to these as DOE-funded patents or simply as DOE patents.

Step B. Identifying HEV/PHEV/EV Battery and Ultracapacitor Patents: In order to identify HEV battery and ultracapacitor patents, we designed a patent filter based on keywords and U.S. Patent Office classifications (POCs). Designing a patent filter such as this is an iterative process, in which various combinations of keywords and POCs are considered in order to generate a suitable patent set. Elements of the filtering system are as follows:

POCs – The first stage in designing a patent filter is determining relevant POCs. Many keywords and acronyms have multiple meanings according to the technology they describe, so it is important to focus on the correct application of these keywords. For example, the term "battery" has a specific meaning in electrical devices and appliances. However, the term could also be used in medicine to describe a battery of tests, or in military applications to describe multiple pieces of artillery. We identified a number of POCs that are particularly relevant to HEV/PHEV/EV batteries and ultracapacitors. These POCs are listed in Appendix A, Table A-1, and their selection is discussed further there.

Keywords – Having generated a list of relevant POCs, we then selected keywords to identify HEV batteries and ultracapacitors. In the process of identifying relevant battery patents, we found that, once the search was restricted to the relevant POCs, the term "battery" has little discriminatory power, such that adding a battery keyword did not narrow certain sets to patents relevant to HEV/PHEV/EV applications. We therefore used keywords related to specific types of batteries that are used, or have been proposed for use, in hybrid and electric vehicles. These keywords are listed in Appendix A, Table A-2, and their selection and effect on the search are discussed further in Appendix A.

As a result of the filtering process, we identified 1,670 U.S. patents issued since 1976 that are related to batteries and ultracapacitors with potential applications in HEVs, PHEVs, or EVs.

2.1.5 Linking HEV, PHEV, and EV Battery/Ultracapacitor Patents to the DOE-funded Patent Set

Our analysis approach centered on linking the identified HEV, PHEV, and EV battery/ultracapacitor patents identified in Step B of Section 2.1.4 to the DOE-funded patent set identified in Step A of Section 2.1.4. This initial linking identified 71 DOE-funded patents directly contained within the HEV/PHEV/EV battery/ultracapacitor filter.

However, further analysis identified additional DOE-funded patents — including those describing inventions covering component technologies such as electrolyte compositions, polymer electrodes and ceramic materials, as well as those describing alternative forms of HEV supplementary power — that, though they were not directly in the group of 71 selected by the filter process, were found to have been cited by the population of HEV/PHEV/EV battery/ultracapacitor patents. In all, 222 different DOE-funded patents were found to have been cited by the HEV, PHEV, and EV patents.

2.1.6 Analyzing and Comparing DOE's Patenting Results with Those of Other Organizations

At the organizational level, the study compares patenting results for DOE to those of other leading organizations active in this technology area — mainly Japanese companies for whom determining their patent sets was more straightforward than for DOE. It should be noted that the patent lists for these other organizations are complete. In fact, the process for DOE was designed to produce a patent list as accurate as the lists for the other organizations. Thus, the comparisons made are valid, rather than partial.[4]

The comparative analysis reveals the organizations with the largest number of patents in the HEV/PHEV/EV battery/ultracapacitor set. It reveals the organizations with the largest number of patents cited by HEV/PHEV/EV battery/ultracapacitor patents. It shows the organizations whose patents are cited most frequently by HEV/PHEV/EV battery/ultracapacitor patents. And, it also shows which organizations have cited DOE-funded patents most frequently.

At the patent level, the study reveals individual DOE-funded patents that have been particularly influential. It identifies the list of HEV/PHEV/EV battery/ultracapacitor patents that cite the largest number of DOE-funded patents. It also reveals highly cited patents from other organizations that have built on DOE-funded patents, and it identifies DOE-funded patents that are most frequently cited by HEV/PHEV/EV battery/ultracapacitor patents.

The results of the patent citation analyses and comparisons allow conclusions to be drawn about influences of DOE's R&D on the targeted downstream innovations that have occurred through patents and their citations. The patent citation analysis — together with the results of the interviews, document reviews, licensing assessment, and institutional analysis — help to inform DOE's role in forming a foundation for HEV/PHEV/EV battery/ultracapacitor technologies.

2.2 Study Limitations

All evaluation methods have limitations. Historical tracing and patent citation analysis, the evaluation methods used in this study, are no exceptions. A clearer picture emerges from the use of the methods in combination, as was done in this study. Yet, limitations remain and the study results are imperfect.

2.2.1 Limitations of Historical Tracing, Supported by Expert Opinion and Document Review

In historical tracing, documentation of linkages across time does not prove cause and effect, although it does provide evidence of relationships. Many factors go into producing a commercially successful innovation beyond those that are traced. There are linkages that tend

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[4] 1790 Analytics LLC tracks these organizations in terms of mergers/acquisitions, etc., and maintains accurate patent lists for them, It licenses these accurate lists to Delphion for its Corporate Tree.

not to be captured by an historical tracing study, even with citation analysis added, such as flows of information along informal lines, information transferred by reverse engineering, and information flows by means that are held confidential, as may be the case with some licensing agreements.

Reliance on expert opinion has the shortcoming that the person interviewed may not be aware of a connection, may not know the specifics, or may believe a connection exists when it actually does not. Significant events may be overlooked, forgotten, or misunderstood. Interviews with additional experts may reveal different perspectives and information. Beyond this, not all the DOE-funded companies identified by experts were examined in detail and not all the instances of assistance and licensing opportunities identified by national laboratory experts were included.

A review of documents, while useful for compiling supplemental evidence, is generally unreliable for developing a full picture of linkages. Some relevant events are reported in documents; some are not. Some documents are preserved; others are not. Available documents tend to provide only partial coverage of long and complex paths over which linkages occur.

Another limitation faced by this study is that the target innovations — the HEV, PHEV, and EV are emerging at different speeds, with the current HEV further along than the others. While the commercialization of the HEV is sufficiently advanced to support a backward tracing from specific downstream commercialized innovations to upstream R&D, development of the next generation of HEVs, PHEVs, and EVs are still underway. Although competition among competing energy storage technologies for these emerging applications is narrowing, it is not yet clear which systems will be selected for production models. In this case, the tracing is, by necessity, between earlier R&D and potential innovations still in the prototype or demonstration stages, with attendant uncertainty.

2.2.2. Limitations of Patent Citation Analysis

With respect to the patent citation analysis, there are several limitations. One limitation is that not all knowledge of significance is embodied in patents. For example, the role of test protocols would not be reflected in patent data — although it was identified by expert review and document analysis as an important linkage. Another is that not all patents are equal; not all citations are equal; not all patents lead to commercial implementation. A further limitation in the case of batteries is that they are relatively complex with multiple patents covering different aspects of battery technologies.

Yet another limitation is that not all patents reveal their ultimate sources of support. Identifying patents funded by government agencies is often more difficult than identifying patents funded by companies. A government agency may fund research in a variety of organizations. As noted previously, the DOE national laboratories are managed by a variety of organizations including universities and companies, and this can complicate a patent search. DOE also funds research carried out by private companies and universities, much of which in the case of energy storage was channeled through the USABC consortium. If this research resulted in patented inventions, these patents are likely to be assigned to the company carrying out the research, rather than to DOE or the USABC. The companies often failed to note government interest in their DOE-supported patents, particularly when the funding was channeled through USABC. This failure increased uncertainty about which patents were at least in part attributable to DOE funding, and has likely resulted in an understatement of the linkages of DOE-supported research to downstream battery and ultracapacitor technologies for HEV/PHEV/EV applications.

Resource and time limitations made it necessary to focus the citation analysis on patent citations. The decision to feature patent citation analysis over publication citation analysis reflects the fact that publications are likely another degree removed from battery and ultracapacitor technologies for vehicles than are patents.

Finally, while the documented citations and other linkages provide evidence of connections between DOE's research and battery and ultracapacitor technologies for hybrid and electric vehicles, and suggest value, they do not provide a dollar measure of the economic benefits of the connections nor prove specific cause and effect.

Chapter 3. Technical and Market Overviews

3.1 HEV, PHEV, and EV Technology Overview

> *Conventional HEV technology is the only one [among HEV, PHEV, and EV] mature enough for its market growth to have an impact on the nation's energy usage in the next 10 years. Pending significant improvements in battery technology, plug-in hybrids could possibly start making an impact in about 10 years, while vehicles powered by fuel cells are unlikely to enter high-volume production in less than 20 years.* (Anderman, Senate Committee Briefing, January 26, 2007, p. 8.)[5]

HEV, therefore, is the innovation of prime interest for this study, because commercial availability or near availability is an essential element in a backward-oriented historical tracing study such as this.

3.1.1 HEV

An HEV combines a 30- to 70-kW electric motor with, most typically, a gasoline-powered internal combustion engine (ICE). This energy storage technology allows downsizing of the ICE and recapture of energy normally lost during braking. An HEV takes advantage of the fact that a conventional ICE has much more power than is needed most of the time; often only a fraction of the available horsepower is needed. Thus, the HEV pairs a smaller ICE with an electric motor to work in tandem, with the electric motor delivering extra power when needed, allowing the ICE to shut off at intervals to conserve fuel. Further, the electric motor functions as a generator to capture the braking energy that would otherwise be lost as heat, and to recharge the battery. This approach increases the miles per gallon of fuel consumed. While all HEVs improve fuel economy over their conventional counterparts, the mile-per-gallon gain can vary depending on the type of HEV, the driving style, and whether driving is mainly in the city or on the highway.

The current degree of hybridization of HEVs ranges from micro-hybrids, to mild hybrids, to moderate hybrids, to strong or full hybrids. The later by far is the dominant form.[6] At the lower end of the range, the micro-hybrid has a beefed-up starter, savings of fuel when the vehicle is idling, and capturing of mechanical energy during braking. Next in line, the mild hybrid uses the electric motor to assist the gasoline engine when it needs supplementary power, such as when passing or climbing a steep grade, but relies on the engine to power the vehicle at all times. The Civic Hybrid, Honda Insight, and GM's Saturn VUE are examples in this category. Strong or full hybrids use the electric motor to propel the car at low speeds (up

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[5] Menahem Anderman, Total Battery Consulting, "Status and Prospects of Battery Technology for Hybrid Electric Vehicles, Including Plug-in Hybrid Electric Vehicles," Briefing to the U.S. Senate Committee on Energy and Natural Resources, January 26, 2007, p. 8.

[6] Highlights of "The 2006 Advanced Automotive Battery Industry Report," April 30, 2007, available at www.advancedautobat.com.

to about 25 mph), and, in addition, to assist the gasoline engine when more power is needed at higher speeds. The Toyota Prius and the Ford Escape Hybrid are examples of strong hybrids.

All of the hybridized categories further increase fuel economy by allowing the engine to shut off while idling and during deceleration. They capture electrical energy through regenerative braking. In all cases, the batteries have the advantage of self-recharging.[7]

The strong hybrid tends to get its best mileage in city driving; the mild hybrid tends to get its best mileage on the highway. The mild hybrid uses a simpler and less expensive hybrid system that achieves modest miles-per-gallon (mpg) improvements. The full hybrid uses a more sophisticated, more expensive hybrid system that achieves higher mpg improvements. Hybrids currently on the market use batteries with rated capacities of 0.6 to 2.0 kWh, of which about 10 percent is used frequently; up to an additional 30 percent is accessed under extreme driving conditions; and the remainder has the primary purpose of ensuring adequate service life.[8]

3.1.2 PHEV

The PHEV "is an HEV with the ability to recharge its energy storage system with electricity from the electric utility grid... electricity generated using alternative domestic resources, or a diverse mix which may include coal, natural gas, wind, hydroelectric, nuclear power, and solar energy."[9] It is sometimes called a "grid-connected hybrid" to emphasize the fact that part of the energy comes from the electric utility grid by plugging into a standard 120-volt home electrical outlet for recharging. Not only would using electricity from the utility grid reduce reliance on imported oil, but it is expected to cost much less than the gasoline needed to travel an equivalent number of miles, particularly if the battery is recharged overnight when demand is lower. Moreover, as shown by Figure 3-1, emissions are expected to decrease more with PHEVs than with HEVs, with both offering improvements over conventional vehicles.

The PHEV has also been called "an electric car with an insurance policy — a gas engine."[10] It can operate in the electric-only mode, in a blended or mixed mode, or in an ICE-only mode. The blended mode makes sense because to go longer and farther on electric power alone would require a bigger, more costly battery which needs to be charged and discharged more completely, as well as a larger ICE.[11] In the blended mode, the engine will come on from time-to-time to supplement the electric motor, and when the battery has been drawn below a certain level, it will provide assistance to the engine as is done currently in HEV modes. The battery will start out at less than 100 percent charge to allow for regenerative braking and will not fully deplete as regenerative braking continues to provide recharging.[12]

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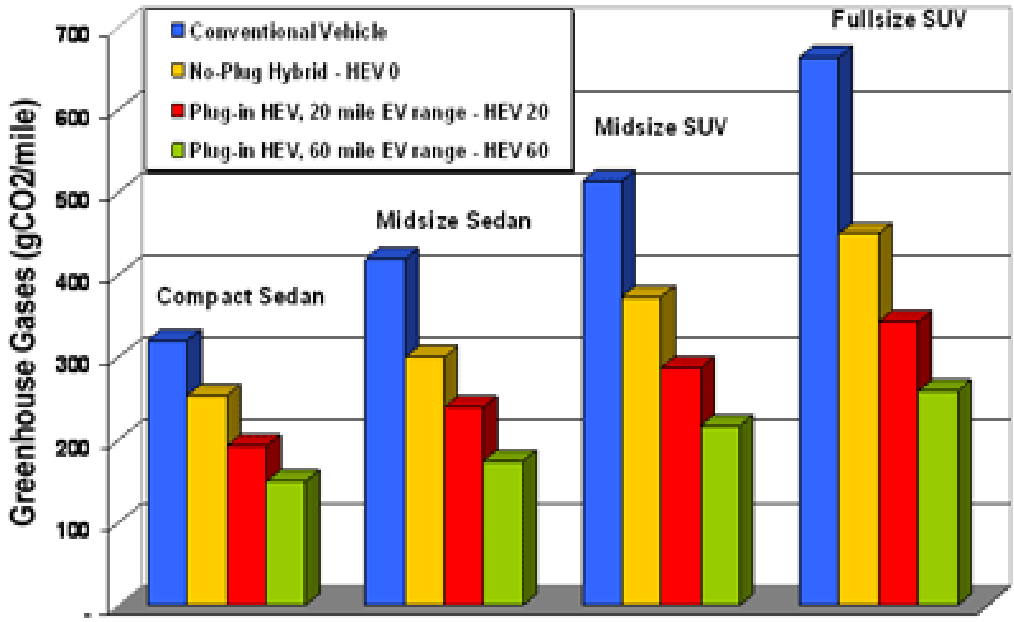
[7] "How a Hybrid Works," Edmonds.com.
[8] Menahem Anderman, 2007, p. 3.
[9] Markel and Simpson, 2006, p. 2.
[10] James Woolsey, former CIA Director, quoted by Plug In America, an advocate group for PHEVs.
[11] "Plug-in Hybrids: What is the State of the Art?" Toyota's *Hybrid Synergy View Newsletter*, Winter 2007 (www.toyota.com/html/hybridsynergyview/2007/winter/plugin.html).
[12] Description of blended mode use was provided by Mr. Gary Henriksen, Manager, Battery Technology Department, Chemical Engineering Division, Argonne National Laboratory, March 5, 2007.



Source: Electric Power Research Institute (EPRI) study, as reported by Plug-In Partners; and also by Lucy Sanna, "Driving the Solution; The Plug-In Hybrid Vehicle, *EPRI Journal*, Fall 2005.

Figure 3-1. Comparison of "well-to-wheels" greenhouse gas emissions for conventional and hybrid vehicles

Although an actual comparison would need to take into account a number of factors, roughly speaking, the PHEV offers about twice the fuel economy of a conventional vehicle. It offers 20 percent to 60 percent higher fuel efficiency than a non-plug-in HEV.[13]

3.1.3 EV

The EV, also sometimes called the BEV (Battery Electric Vehicle), is a fully electric vehicle, with no backup or supplementary non-electric engine. When the mileage capacity of the battery is exhausted, the vehicle stops, and the battery must be recharged by plugging into the electric utility grid.

Advantages of the EV are that it offers the potential of zero gasoline use and very low emissions, the amount depending on the power source of the utility plant producing the electricity to recharge the EV. In any case, using utility-plant-generated electricity to power the vehicle, as noted previously, would be expected to reduce dependence on imported oil because only about 3 percent of electricity in the United States is generated from petroleum.[14]

A disadvantage of the EV is that it is characterized by a limited driving range, which though it may be several hundred miles, may fall short of driving demands. A major battery-related challenge for the EV is to provide a driving range performance before recharging that is

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[13] "Plug-In Hybrids," www.pluginamerica.com and www.pluginpartners.org.

[14] Brent D. Yacobucci, CRS Report RL30484, *Advanced Vehicle Technologies: Energy, Environment, and Development Issues*, December 17, 2004, p.2.

comparable to that of the ICE (approximately 300 miles) before refueling becomes necessary. To recharge the battery pack of an EV can take on the order of four to eight hours and the need to recharge can occur on the road, thus challenging the nation's infrastructure as well as the driver's schedule and convenience. The battery packs are heavy and take up considerable vehicle space.[15] EV battery cost is still high and lifetimes are still relatively limited. Furthermore, power outages may make it impossible to recharge an EV, which becomes more limiting in the face of having no backup system.[16] The EV offers more technical and other challenges than the PHEV and HEV, vehicles which ask less of their energy storage systems.

3.2 HEV, PHEV, and EV Market Overview

3.2.1 HEVs — a Fast Growing Share of Auto Sales Since 1999

Since the first HEV was introduced in the United States in 1999[17], sales of the HEV have grown at an average annual rate of more than 80 percent per year.[18] From 2004 to 2005, the annual rate of increase in sales rose to more than 139%.[19] In 2006, purchase of HEVs by U.S. consumers reached 254,545, comprising about two-thirds of world sales of HEVs.[20] Based on the numbers of registered hybrids, Los Angeles, New York, Boston, and Washington, D.C. are considered "hybrid hot spots" as of early 2007.[21]

The world hybrid vehicle market in 2006 was estimated at 384,000 vehicles, projected to reach 1.1 million units in 2010. Toyota held 78 percent of the world hybrid vehicle market in 2006, followed by Honda, Ford, and General Motors.[22] Cumulatively, slightly more than half of Toyota's global million-plus HEVs sold were sold in the United States.[23]

Figure 3-2 shows hybrid vehicle sales in the United States by model from 1999 to 2006. It shows the dominant position of the Toyota Prius over this period, but it also shows the recent increasing share of sales by other models. By early 2007, HEV models on the market included, from Ford, the Escape Hybrid and the Mercury Mariner Hybrid; from GM, the Chevrolet Silverado, the GMC Sierra, the Saturn VUE and Aura Green Line; from Toyota, the

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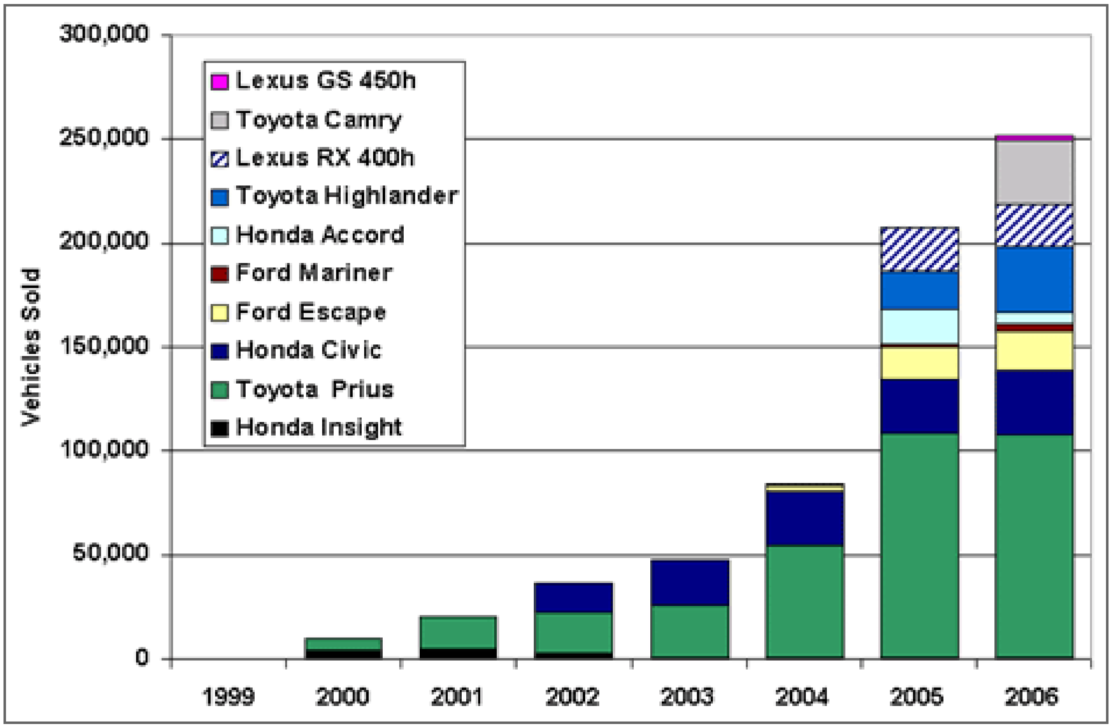
[15] "Electric Vehicles," www.fueleconomy.gov.
[16] As another dimension to power supply, there is interest by some companies in enabling PHEVs and EVs to deliver electricity back to the house or to the grid, providing more versatility, and utilizing the vehicle as an energy source. (Kevin Bullis, "Electric Cars: What Happens When the Power's Out?" *MIT Technology Review*, January 18, 2007.)
[17] The first modern hybrid, the Honda Insight, was introduced in the United States in December 1999, but actually the first hybrid (but without integration of the engine and the electric motor) was introduced in the United States in 1916 by the Woods Motor Vehicle Company of Chicago. (Tara Baukus Mello, "Hybrid Popularity Skyrockets," May 17, 2006, www.Edmonds.com.)
[18] Markel and Simpson, 2006, p. 1.
[19] R.L. Polk and Company, cited by Bengt Halvorson, "Hottest Hybrids for 2007," www.forbesautos.com.
[20] The Associated Press, "Sales of Hybrid Cars Increase," September 17, 2007.
[21] Bengt Halvorson, "Hottest Hybrids for 2007."
[22] World market estimates and market shares of automakers are from highlights of "The 2007 Advanced Automotive Battery Industry Report," April 30, 2007, available at www.advancedautobat.com.
[23] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Vehicle Technologies, Fact of the Week, #476, July 2, 2007, "One Million Toyota Hybrids Worldwide." (www1.eere.energy.gov/vehiclesandfuels/facts/2007_fcvt_fotw476.html.)

Prius, Camry, and Highlander; from Toyota's Lexus division, the Lexus GS450h and RX 400h; from Honda, the Accord, Civic, and Insight; and from Nissan, the Altima hybrid.[24]

More hybrids are reportedly on the way.[25] While Ford, GM, Honda, Mercury, and Toyota already have HEVs on the market and are planning more, Chrysler, Hyundai, Kia, and Mitsubishi have HEVs in development, and Porsche, Subaru, Volkswagen, Daimler's Mercedes-Benz Division, and Ford's Volvo Cars are reportedly considering putting HEVs into production.[26] GM, Chrysler, and BMW agreed in 2005 to become equal partners in a hybrid development effort.[27]



Source: DOE/EERE's Vehicle Technologies Program, Fact of the Week, #462, March 26, 2007, "Historical U.S. Hybrid Vehicle Sales."

Figure 3-2. Hybrid vehicle sales in the U.S. by model, 1999-2006

J.D. Power-LMC Forecasting predicts that there will be 38 hybrids on the market by 2011.[28] Ford, for example, has announced that it will bring hybrid power to half of its vehicles over the next five years.[29] The availability of more models and body styles, more mainstream designs

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[24] "New Car Pricing: Hybrids," www.Edmonds.com.
[25] Jim Press, President of Toyota Motor Sales U.S.A. was quoted as saying that Toyota alone plans to introduce 10 new HEV models over the next 5 years, and expects that HEVs will represent 25 percent of its U.S. sales by the end of the decade, meaning an estimated 600,000 new HEVs annually, at its current rate of sales, just from Toyota. (Tara Baukus Mello, "Hybrid Popularity Skyrockets," May 17, 2006, www.Edmonds.com.)
[26] Ibid.
[27] Joe Benton, "BMW Joins GM, DaimlerChrysler Hybrid Project," www.ConsumerAffairs.com
[28] Ibid.
[29] Ron Cogan, "Is a Hybrid in Your Future?" www.forbesautos.com.

aimed at a broad range of buyers, improved performance, and higher fuel prices have led to what market researchers have termed skyrocketing popularity of hybrids.[30]

3.2.2 PHEVs — Still in Concept Stage But Expectations are High

At the time of the study, the PHEV had not yet reached consumer markets — except through conversions of HEVs into PHEVs[31] and as prototypes or demonstration models. However, the PHEV is of growing interest because it offers the potential to displace a larger share of the consumption of petroleum for transportation than the HEV, while taking advantage of practicality and favorable cost tradeoffs.[32]

Because the PHEV has more battery capacity than the HEV — with a range on the order of 20 to 60 miles without the use of gasoline and without recharging — a PHEV has the potential to meet a large percentage of the American public's daily driving requirements, and for that reason is attracting growing interest. Figure 3-3 shows the percentage of American automobiles that drive different daily mileages. From the resulting curve, one can estimate the percentage of driving by the American public that potentially could be met by PHEVs having various mileage capacities from a plug-in charge. For example, a PHEV capable of 40 miles per day on the battery without recharging would potentially meet the daily needs of about 60 percent of the American driving public.[33]

A national manager in Toyota's Advanced Technology Group concluded that none of the PHEV systems thus far demonstrated meet all the challenges of commercial acceptability — challenges that include size, weight, performance, durability, and cost.[34] However, if the previously mentioned advantages are recognized by consumers, and the remaining technical challenges facing the energy storage system — particularly challenges of cost and life cycle — can be overcome, PHEVs may become a growing component of the U.S. vehicle mix in the future.[35]

In early January 2007, GM's Chevrolet Division introduced a prototype PHEV, the Chevrolet Volt, but without a date when it will be available for purchase by consumers. The Volt is envisioned to have an all-electric range of 40 miles, making it possible for many to perform most daily driving without using any gasoline.[36] At the same time, Ford presented a prototypical display of its HySeries Drive PHEV.[37] Toyota reportedly is seriously working on

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[30] Tara Baukus Mello, "Hybrid Popularity Skyrockets," May 17, 2006, www.Edmonds.com.
[31] Conversions of existing hybrids, such as the Prius, to accept plug-in charging is expected to increase from a few dozen to hundreds per year, but conversion is not considered by the DOE research community or by this study as providing a market-ready PHEV. At the same time, it is recognized that a growing conversion market may speed development of PHEV production by the larger automotive manufacturers.
[32] Markel and Simpson, 2006, p. 9.
[33] Ibid.
[34] "Plug-in Hybrids: What is the State of the Art?" Toyota's *Hybrid Synergy Newsletter*, Winter 2007 (www.toyota.com/html/hybridsynergyview/2007/winter/plugin.html).
[35] Interview with Dr. Philip Patterson, EERE Industry Economist, October 19, 2006.
[36] Marta Wells, "GM Unveils Plug-In Electric Car," January 8, 2007, http://business.knowmoremedia.com/2007/01/gm_unveils_plugin_electric_car.html.
[37] Warren Brown, "A Visionary Plugs in to the Electric Car Race," *Washington Post*, January 9, 2007, p. D03. (www.washingtonpost.com/wp-dyn/content/article/2007/01/08/AR2007010801542.html?sub+new)

a plug-in Prius.[38] The Electric Power Research Institute (EPRI) and Chrysler have a joint trial for converting EPRI's Sprinter vans into plug-ins.[39]

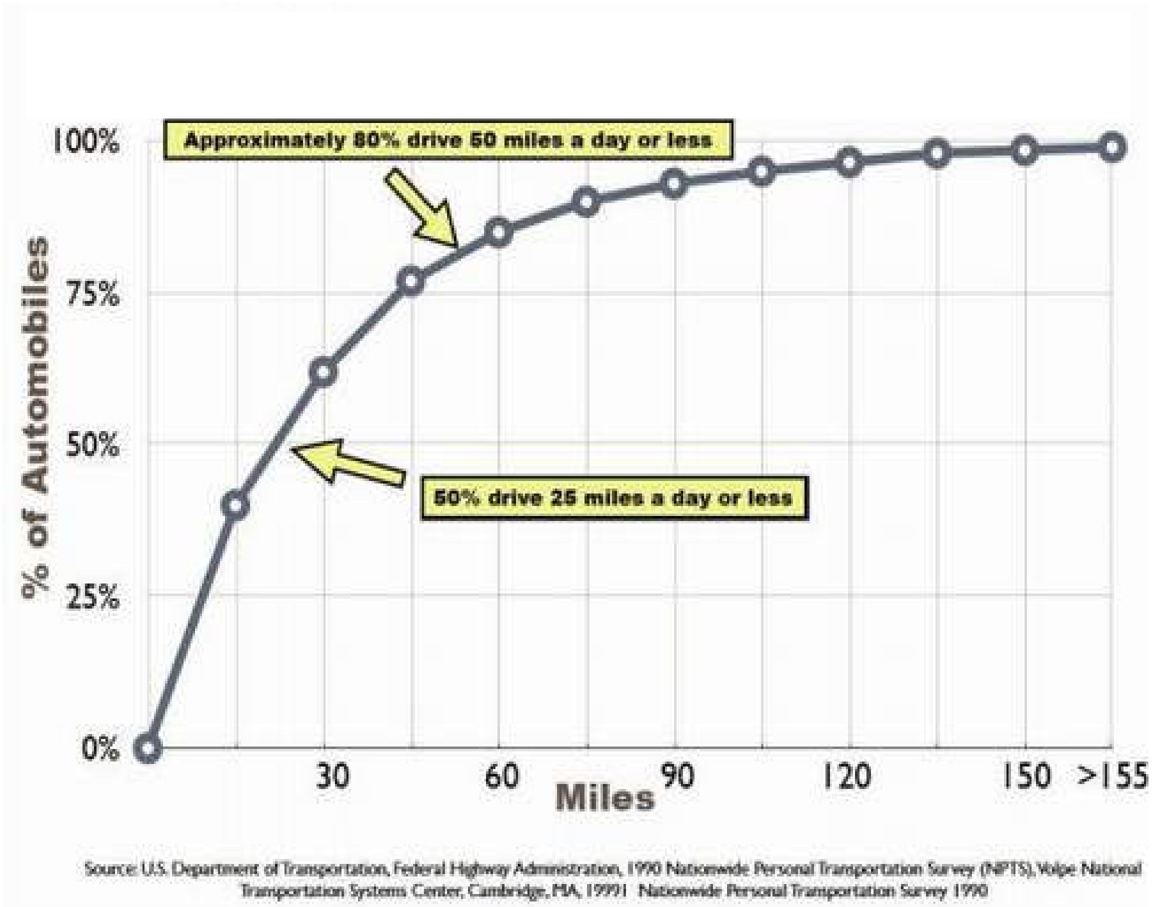

Figure 3-3. Percentage of Automobiles by the Number of Miles Driven Daily by the American Public[40]

The barrier is that the advanced Li-ion batteries needed to power the PHEV are not yet market ready. Both GM and Ford officials have been quoted as saying that their companies are at least a decade away from affordable, reliable lithium batteries needed to make their PHEVs market feasible.[41, 42] At an Automotive News World Congress early in 2007, a conference speaker, Nancy Gioia, spoke of the interest of automakers in adding PHEVs to their product lines, but emphasized that the biggest barrier is the battery.[43] At the same time, there are

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[38] "Plugging into the Future," *The Economist*, June 8, 2006.
[39] Ibid.
[40] The figure, prepared from a U.S. Department of Transportation survey data, was found at www.pluginamerica.com, an advocacy group for PHEV.
[41] Warren Brown, "A Visionary Plugs in to the Electric Car Race," *Washington Post*, January 9, 2007, p. D03.
[42] Prior to its breakup early in 2007, DaimlierChrysler reportedly had a modified plug-in version of a large van, however, according to DOE/EERE research managers interviewed, PHEVs currently available are individually modified from HEVs, and are not "true" PHEVs.
[43] "Ford mulls plug-in hybrid vehicle," CNNMoney.com, January 16, 2007.

visionaries outside the major auto companies who hold out the possibility of developing affordable PHEVs in a shorter time.[44]

3.2.3 EV — Early but Fading Attention for Near-Term Solutions

Electric vehicles date back at least 100 years, and for a while were actually more prevalent than gas-powered vehicles. By 1920, however, the gasoline-powered ICE had won out, and the electric car faded from use.

Then, during the 1990s, automakers manufactured an estimated 5,000 EVs in response to California's Zero Emission Vehicle Mandate.[45] GM introduced an all-electric car, called the EV1, as early as 1990. Toyota introduced a RAV4-EV. Ford offered its Ranger Truck as an EV. Few of these vehicles were ever offered for sale to consumers; rather, they were made available in California chiefly through leasing agreements. In addition, an estimated ten thousand conventional cars were converted to electric propulsion by small shops and individual owners, again prompted by California's Mandate.[46] The EVs of that time generally used lead-acid batteries which were cheap and safe but short on range and life. By the early 2000s, most of the EVs had been repossessed by the auto companies, hauled away, and crushed.

A variety of factors have been suggested as contributing to the collapse of the EV during the 1990s. Recent press coverage of GM's unveiling of its new Chevrolet Volt, electric plug-in car, included the statement that GM dropped its previous electric vehicle of the 1990s after corporate officials balked at more than $300 million for further development.[47]

A National Research Council (NRC) committee concluded that GM stopped production of its EV-1 car due to poor customer acceptance.[48] Others said that California's Zero Emission Vehicle Mandate was out of touch with the market, resulting in artificially created and propped-up businesses, which, in the face of a backing away of California officials from the initial mandate, resulted in a collapse of the EV business. Some pointed to the inadequacy of the energy storage system[49] — a principal factor behind the need for further large development costs. Still others pointed to a growing belief that the most viable path to reducing petroleum use and emissions, at least in the near term, lay in hybridization rather than in fully electric vehicles.[50]

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[44] Among them is Malcolm Bricklin, Chairman and CEO of Visionary Vehicles, this according to Warren Brown, "A Visionary Plugs into the Electric Car Race," *Washington Post*, January 9, 2007.
[45] To sell cars in California, producers had to sell a certain percentage with zero emissions.
[46] U.S. Electric Auto Association.
[47] Sholnn Freeman, "GM Introduces Plug-In Electric Car," *Washington Post*, January 8, 2007, p. A07.
[48] NRC, Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, *Energy Research at DOE, Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000* (2001) (Washington, DC: National Academy Press, p. 141).
[49] "Plugging into the Future," *The Economist*, June 8, 2006.
[50] Bill Moore, "Report on March 27–28th California Air Resources Board Meeting (excerpts)," March 29, 2003, *EV World*.

Yet another factor that was offered in explanation for the move away from the EV in the 1990s was that there was too much money to be made with the technological stagnation of the internal combustion engine.[51] GM officials in interviews cited inadequate demand, while EV advocates argued that there were waiting lists for the car.[52] Skeptics pointed out the lack of supporting infrastructure, the high prices of the vehicles, the use of a lead-acid battery with a limited range before recharging, and environmental concerns that electric utilities used for recharging might be fueled by coal, resulting in higher emissions. GM, Chrysler, and other car manufacturers sued California over its emission mandate, and the state revised its mandate to incorporate reduced goals. Thus, California regulators relaxed pressure on automotive manufacturers to supply EVs, and this has been pointed to as another contributing factor for the subsequent move away from EVs in the 1990s.[53]

It was noted by others that as of the mid-1990s, U.S. auto manufacturers appeared to be in the lead with respect to electric vehicles, and did not appear to be concerned about foreign competitors. Yet, by the later part of the decade, the foreign competitors had "seized the advantage, turning their electric-car know-how into hybrid cars."[54]

Currently, there are a few small companies — mostly located in California — that are manufacturing, or importing and "Americanizing" electric cars for niche markets. Generally these companies are relatively new; offer a variety of electric vehicles, including scooters, bicycles, and golf carts; and are coming to market with small EVs in small volume.[55] For example, Tesla Motors, Inc., a Silicon Valley automaker that was started in 2003, announced as its first production vehicle, the Tesla Roadster, an EV sports car with a planned range of 250 miles per charge, acceleration from 0 to 60 mph (100 km/h) in 4 seconds, a top speed of 130 mph (210 km/h), and an operating cost-per-mile of about 1 cent, depending on local electricity rates. The EV uses a pack of nearly 7,000 individually wrapped Li-ion batteries,[56] the same kind of batteries used in most consumer-electronics devices, such as laptops, cell phones, and camcorders — only a few more of them.[57] The company advertises that a full charge of the battery takes as little as 3.5 hours, and promotes the idea that the 250-mile range will allow recharging at home. The company introduced the EV in prototype in July 2006 and announced plans to release the first production model in 2007, in a small, fully subscribed edition.[58] As another example, Universal Electric Vehicle Corp (UEV) advertised that it was

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[51] Ralph Nader quoted in "Who Killed the Electric Car," a 2006 documentary film that explores the limited experience with the battery electric vehicle in the United States during the 1990s.
[52] "Who Killed the Electric Car," op cit.
[53] Ibid.
[54] Sholnn Freeman, "GM Introduces Plug-In Electric Car", *Washington Post*, January 8, 2007, p. A07.
[55] A list of EV manufacturers in the United States includes the following: ZAP, Baker Electromotive, Inc., Convergence Tech, Inc., DIDIK, Doran Motor Company, Eco-Motion Electric Cars, Electric Transportation Company, Electric Vehicle Corp, Esarati Electric Technologies Corp, EVI International, Global Electric Motorcars LLC, Laurel Hill Software Company, Me and My EV, That EV LLC, and Wilde EVolutions Inc. Also listed is American Honda Motor Co., Inc. (http://energy.sourceguides.com/businesses/byGeo/US/byB/mfg/byP/ev/ev.shtml)
[56] Individually wrapping the batteries means that if one catches fire, the others are safe. (Lou Ann Hammond, "Are Lithium Ion Batteries Safe for Cars?" September 5, 2006, www.carlist.com.)
[57] The information about Tesla Motors' EV was found at the company's Web site, www.teslamotors.com.
[58] Ibid.

accepting orders in December 2006 on its Electrum Spyder, a two passenger EV in limited production, at a 2007 price of $69,995.

Increasing the mileage capacity of batteries to a range of 300 miles to meet the current envisioned requirements of EVs gives rise to size and cost increases, infrastructure issues, and undesirable changes in other parameters that have had the effect of shifting attention back to the HEV and PHEV as more practical alternatives in the nearer team. There seems to be a growing opinion that, at least in the nearer term, the greatest potential for reductions in use of imported petroleum and related emissions for passenger vehicles lies in improving NiMH and Li-ion batteries for use in HEVs and PHEVs.

3.3 About Batteries — the Make-or-Break Component

A battery provides electrical power by converting energy from a chemical reaction into electrical energy. Advances in energy storage technologies have been, and continue to be, deemed essential to the further development of the HEV, PHEVs, and EVs. Their development has presented a number of research challenges and barriers to commercialization.

When this study was initiated, EERE requested that it begin with an inquiry to scope the energy storage technologies most important to today's HEVs, PHEVs, and EVs, or alternatively their prototype or demonstration models. It was requested that the study then narrow the scope to focus on specific advanced energy storage technologies based on expert opinion. The experts consistently pointed to advanced batteries as of greatest importance, followed by ultracapacitors. By like token, the advice consistently was to not focus on the fly wheel, another energy storage technology.

The battery is the core technology that determines how hybrids and electric vehicles will perform. Price, size, longevity, volatility and safety, and performance under harsh conditions are among persisting key battery concerns. According to Massachusetts Institute of Technology (MIT) Professor Yet-Ming Chiang, a materials scientist who is credited with major advances in battery technology and a co-founder of A123Systems, an advanced battery development company funded by DOE through USABC, "They [batteries] are chemically complex, electrically complex, and mechanically complex."[59] Technical challenges with the battery have proven much more difficult to solve than was earlier expected.

For HEVs, the emphasis is on a battery's power density; for PHEVs, the emphasis is on a battery's energy storage.[60] A battery with high power can deliver a higher burst of power, but stores less energy. A battery with high energy storage stores more energy per unit weight such that it works longer. Batteries in HEVs are cycled in shallow discharges hundreds of

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[59] William M. Bulkeley, "New type of battery offers voltage aplenty, at a premium," *The Wall Street Journal*, November 2, 2005 (www.post-gazette.com/pg/05306/599379.stm). A123Systems is discussed further in Chapter 4.

[60] "Energy" is the capacity of a battery to produce effect; it is usable potential power. "Power" is the rate at which electrical energy is transferred by an electric circuit or expended. Electric energy is usually measured in kilowatt hours (kWh); electric power is usually measured in kilowatts (kW).

thousands of times under a partial charge/discharge regime. A PHEV requires significantly more capacity than exists in the batteries currently used in HEVs. To power a PHEV will require a NiMH battery with more capacity, other things being equal, than is currently available in these batteries in volume production, or a Li-ion battery with more capacity than in existing NiMH batteries.[61]

3.3.1 NiMH Battery

A focus of this study is the NiMH battery because it is the battery generally found in today's HEVs. The NiMH HEV battery market was estimated at $600 million in 2006, and is projected to grow to $1.4 billion by 2010.[62] As the current battery-of-choice for commercialized HEVs, the NiMH battery most closely meets the requirement of a backward tracing study.

The NiMH battery used in today's HEVs is relatively small, has favorable life-cycle characteristics, high power, a light weight, a high level of safety, good thermal performance, and a configurable design. NiMH batteries are battle-tested and safe.[63] In fact, according to a recent congressional briefing, NiMH batteries are the only proven and reliable electric power source for HEVs.

At the same time, they are not an ideal energy-storage device for HEVs. Limitations include some energy loss and heat production in normal usage, reduced life with high depth-of-discharge cycling, and the possibility of unsatisfactory performance at high and low temperatures. The price of NiMH battery packs near the time of the study was put in the range of $600 to $3,000 for an HEV, with the lower end of the price range reflecting a lower energy storage capacity of approximately 0.6 kWh for a battery pack for a mild hybrid, together with the lower end of the pricing range per unit energy storage capacity. The upper end of the price range reflects a higher energy storage capacity of 2.0 kWh for a battery pack for a strong hybrid, together with the upper end of the pricing range per unit energy storage capacity. The estimated range for a NiMH battery pack for a PHEV was $5,000 to $7,000 .[64]

3.3.2 Li-ion Battery

The Li-ion battery is seen as the battery of choice for next-generation HEVs and for PHEVs, and it is being aggressively developed for HEV and PHEV applications. While hybrids that are currently produced use a NiMH battery, it is generally considered an interim battery, soon to be eclipsed by the Lithium Ion battery.[65] Alan Mumby, Vice President and General

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[61] "Hybrid Batteries Q&A," Toyota's *Hybrid Synergy View Newsletter*, Fall 2006 (www.toyota.com/html/hybridsynergyview/20006/fall/battery/htm.).
[62] Highlights of "The 2007 Advanced Automotive Battery Industry Report," April 30, 2007, available at www.advancedautobat.com.
[63] "Plugging into the Future," *The Economist*, June 8, 2006.
[64] Menahem Anderman, "Status and Prospects of Battery Technology for Hybrid Electric Vehicles, Including Plug-in Hybrid Electric Vehicles," Briefing to the U.S. Senate Committee on Energy and Natural Resources, January 26, 2007, p.3.
[65] Lou Ann Hammond, "Are Lithium Ion Batteries Safe for Cars?" September 5, 2006, www.carlist.com.

Manager of Johnson Controls' hybrid battery business, described Li-ion battery technology as ideal for hybrids with regenerative braking and the wave of the future.[66]

Li-ion batteries offer advantages of higher power and energy per unit weight and volume as compared with NiMH batteries. They have a better charge efficiency than NiMH batteries, and they also offer a potential for a longer life and a quicker charge. Perhaps in the future they will even offer lower costs as compared with NiMH batteries due mainly to the rising cost of nickel and cobalt. However, the Li-ion battery's reliability is not yet proven in HEVs, and they are likely initially to have a higher price.[67] Questions have been raised about the safety of Li-ion batteries for automotive applications, particularly given that laptops powered by Li-ion batteries have been recalled due to volatility, explosions, and fires.[68] A current focus of DOE's energy storage R&D — in conjunction with the automotive and battery consortia — is to overcome the chemical and thermal stability challenges of Li-ion batteries under abusive conditions that may arise in automotive applications, and to do it cost effectively.[69]

According to Dr. Manahem Anderman, a battery industry consultant, it is also possible that the increased pressure to reduce the price of batteries has increased the risk of volatility. He points out that while a NiMH battery used in an HEV or PHEV is never fully charged so that it can absorb regenerative braking and therefore is much less volatile, a Li-ion battery for a full EV has to be fully charged and is therefore more volatile. Lithium-ion can be safe for a hybrid, plug-in and, eventually, a full EV, but not on a shoestring budget. Auto manufacturers need to be conservative in their design and manufacturing and robust in their packaging and engineering.[70] In his senate committee briefing, Dr. Anderman further stated:

> *In the United States, significant progress has been made under the auspices of the U.S. Advanced Battery Consortium, a collaborative effort between the U.S. Department of Energy, the auto industry, and battery developers. Following extensive system-verification tests, lithium-ion batteries are still expected to enter the HEV market in two to three years, and their use to grow thereafter, provided no major negative surprises arise. In the longer term — perhaps in about 10 years — accelerated progress may gradually close the gap between the targeted battery requirements for plug-in HEV and the state and cost of battery technology, thus facilitating the introduction of plug-in hybrid vehicles as well.* (Anderman, Senate Committee Briefing, January 26, 2007, pp. 4-5 and p. 8.)

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[66] Mr. Mumby of Johnson Controls, quoted in "Plugging into the Future," *The Economist*, June 8, 2006.
[67] Menahem Anderman, "Status and Prospects of Battery Technology for Hybrid Electric Vehicles, Including Plug-in Hybrid Electric Vehicles," 2007.
[68] There are differences among Li-ion batteries in terms of the materials used and each has its unique problems, ranging from possible thermal runaway for the cobalt Li-ion battery, to a durability problem for the Manganese Li-ion battery, to a lower power ratio for the iron phosphate Li-ion battery. Lou Ann Hammond, "Are Lithium Ion Batteries Safe for Cars?" September 5, 2006, www.carlist.com.
[69] Interview with Mr. Tien Duong, October 20, 2006.
[70] Quoting Dr. Menahem from an article by Lou Ann Hammond, "Are Lithium Ion Batteries Safe for Cars?" September 5, 2006.

3.3.3 Current Suppliers of NiMH and Li-Ion Batteries

Despite strong research programs in the United States and Europe, two Japanese battery producers — Panasonic EV Energy, a joint venture between Toyota Motor Company and Panasonic Batteries (a subsidiary of Matsushita Electric[71]), and Sanyo — together have a more than 85 percent share of today's HEV battery market, which currently is comprised almost totally of NiMH batteries. Moreover, Panasonic EV Energy alone has a more than 75 percent share of this market.[72]

A pattern of U.S. strength in research and Japanese and other Asian nations' strength in high-volume, low-cost manufacturing is by no means limited to the area of batteries.[73] In the late 1980s, for example, congressional concern over the observation that U.S. technological advances led repeatedly to production abroad was a prominent factor prompting creation of federal programs aimed at helping to bridge from research to commercialization in the United States and to strengthen U.S. manufacturing. One such program, the Advanced Technology Program, commissioned a study, published in 2006, which addressed the question of why there were no volume manufacturers of Li-ion batteries for consumer electronics in the United States. The aim was to increase understanding of factors important to decisions about where to locate the commercialization of new innovations researched and developed in the United States and important to delivering benefits world-wide.[74]

In his Senate briefing, Dr. Anderman, battery consultant, recognized this continuing issue in the following words:

> *To the degree that the U.S. Government is interested in supporting the establishment of a domestic supply of HEV batteries, thought should be given to addressing this significant gap in high-volume lithium-ion manufacturing expertise between U.S. developers and their Japanese and Korean counterparts, in addition to supporting the development of battery materials and improved cell design.* (Anderman, Senate Briefing, January 26, 2007, p. 9.)

Recent developments show Cobasys, A123Systems, and JCI-SAFT among those demonstrating potential as future suppliers of Li-ion batteries for next-generation HEVs and PHEVs. Among recent development are advances by A123Systems, a spin-off from MIT, in a new lithium battery that combines a novel Li-ion phosphate chemistry with nanoscale materials that offer lower volatility, as well as the potential for lower cost and longer life. Reportedly A123Systems plans to supply Hymotion, a Canadian firm that supplies kits for converting HEVs to PHEVs, with its batteries for PHEVs, and has a manufacturing capacity to

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[71] On January 10, 2008, Matsushita Electric announced that on October 1,, 2008 it will change its name to Panasonic Corporation.
[72] Highlights of "The 2007 Advanced Automotive Battery Industry Report," April 30, 2007, available at www.advancedautobat.com.
[73] Based on the volume of battery patents issued to Japanese companies, it appears these companies also have played an active role in battery R&D.
[74] Ralph J. Brodd, *Factors Affecting U.S. Production Decisions: Why Are There No Volume Lithium-Ion Battery Manufacturers in the United States*, NIST GCR 06-903, Dec. 2006.

make 10,000 batteries a year.[75] Acquiring production facilities abroad is among the strategies of U.S.-based companies to accomplish volume battery production.

3.4 Ultracapacitors

An ultracapacitor is another type of energy storage device. Like a battery, it is an electrochemical device; however, unlike a battery which stores energy electrochemically, an ultracapacitor stores energy electrostatically. An ultracapacitor has no moving parts and a very long lifespan. Although an ultracapacitor stores much less energy than a battery, it can release energy in quick bursts faster; i.e., with more power, than a battery.

3.4.1 Use of Ultracapacitors

An ultracapacitor may be used as a supporting energy storage device to a battery to provide short power pulses such as needed for HEV power assist during acceleration and climbing hills. It can capture and store electrical energy generated by braking and release it quickly for reacceleration.[76] An ultracapacitor may also be used alone to serve as a supplementary power source to a main power source, such as a fuel cell stack.[77]

As a supplement to batteries in an HEV, ultracapacitors offer benefits. In addition to increasing available energy by providing high peak power when needed and improving fuel efficiency under stop-and-go driving conditions, using an ultracapacitor in conjunction with a battery also can extend battery life, reduce maintenance and replacement costs, and enable downsizing of the battery. These benefits, however, come at a higher vehicle initial cost because the current cost of ultracapacitors is high and combining ultracapacitors and batteries requires additional electronics.[78] While it is not yet a mature technology, the ultracapacitor is of intense interest for its potential use in future vehicles.[79]

3.4.2 Current Suppliers of Ultracapacitors

The leading manufacturers of ultracapacitors are Maxwell Technologies in the United States, NESS Capacitor Company in South Korea, Okamura Laboratory in Japan, and EPCOS in Europe. They embody proprietary differences.[80]

In 2005 and 2006, Maxwell Technologies, Inc. (NASDAQ: MXWL) introduced compact, fully integrated, ultracapacitor modules, first a 48-volt module followed by a 125-volt module, thereby providing easy-to-integrate building blocks for scalable energy storage and power delivery solutions for heavy hybrid and electric vehicles (bus, truck, and electric rail vehicles)

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[75] "Plugging into the Future," *The Economist*, June 8, 2006.

[76] Background information about ultracapacitors was found at the National Renewable Energy Laboratory site, www.nrel.gov/vehiclesandfuels/energystorage/ultracapacitors.html.

[77] The performance characteristics of ultracapacitors and fuel cells are reportedly highly complementary, especially for powering vehicles in stop-and-go traffic. For example, Honda Motor Company is using ultracapacitors in its FCX hybrid fuel cell vehicle, now in the test model stage. (http://world.honda.com/FuelCell/FCX/ultracapacitor/)

[78] www.nrel.gov/vehiclesandfuels/energystorage/ultracapacitors.html.

[79] Advanced Automotive Batteries, "The Ultracapacitor Opportunity Report (Description)" www.advancedautobat.com/Utracapacitor/index.html.

[80] John M. Miller, "Ultracapacitors Challenge the Battery," www.worldandi.com.

and heavy duty industrial applications. The module is said to perform reliably through one million or more deep charge/discharge cycles, which equates to more than 15 years of operational life.[81]

According to Maxwell Technologies, explaining the opportunity potential of ultracapacitors:

> *When capacitors can store as much energy as batteries while avoiding much of the environmental threat posed by the metals (such as lead, nickel, cadmium, and mercury) required to run the battery's electrochemical process, a new era of energy for transportation will begin. Costs, of course, will need to come down, and the devices will need to be proven functional and highly reliable in daily use.* [Maxwell Technologies' Web site available at: www.maxwell.com/about-maxwell/facilities-manufacturing.asp.]

3.5 Batteries and Ultracapacitors Then and Now

Showing change over the past 30 years does not prove that DOE's energy storage R&D caused the change, rather than other factors. At the same time, if a program makes a difference, something should change relative to what it otherwise would have been.[82] Making a comparison of the status of energy storage technology at the beginning and end of the period of DOE-supported R&D highlights that change has occurred over this period. Demonstrating that DOE-funded R&D is linked to the downstream innovations in batteries and ultracapacitors for hybrid and electric vehicles provides evidence that DOE played a role in the change.

Back in the late 1970s, upon the formation of DOE's R&D program in advanced energy storage, efforts were underway for improving lead acid batteries for EVs in the areas of energy density, recharging time, maintenance, and other performance aspects. DOE's program was largely independent of industry input. Also, there were no standard test protocols that were widely accepted for evaluating batteries.

By 2007, the end of the period examined, battery technology had moved far beyond the lead-acid days of the late 1970s. With the shift to hybridization in the late 1990s and the emergence of HEVs, NiMH batteries were established as the baseline battery technology. By the mid-2000s, next generation HEVs and PHEVs were seen as the most promising near-term direction for reducing imported oil needs for transportation and attendant emissions, and the focus was on batteries for these vehicles. Li-ion batteries had advanced in terms of performance, weight, and cost improvements, and were emerging for use in vehicles in the relatively near term. The projected cost of baseline 25-kW Li-ion battery systems had been reduced from $1,750 and

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[81] John M. Miller, vice president, advanced transportation applications, quoted in a Maxwell Technologies Press Release, "Maxwell Technologies Introduces 125-Volt BOOSTCAP® Ultracapacitor Module for Heavy Hybrid and Electric Vehicles," November 14, 2006.

[82] Conditions for establishing cause and effect are presented by Padma Karunaratne and Rosalie Ruegg, On-line Evaluation Course, Module 3: Monitoring and Evaluating (M&E) Publicly Funded R&D Programs--Study Design, (Demonstration presented at the American Evaluation Association Conference, October 2005).

$70/kW in 1999, to $1,200 and $48/kW in 2003.[83] Furthermore, the price differential of HEVs over their counterpart conventional vehicles had narrowed considerably, and the battery market for HEVs was on a steep growth trajectory as sales of these vehicles rose. The use of standard test protocols for benchmarking batteries for HEVs, PHEVs, and EVs from suppliers the world over had become enabled, feasible, and common practice.

Flywheels and ultracapacitors attracted early attention as energy storage technologies for vehicles, before falling out of favor. More recently, ultracapacitors have again gained attention as potential power sources for vehicles.

3.6 Advances in Other Technologies

The focus of this study on advances in battery and ultracapacitor technologies for HEVs, PHEVs, and EVs that are linked back to DOE's research is not to diminish the contributions of other research efforts of DOE also aimed at advancing the potential of HEVs, PHEVs, and EVs. To provide a broader context within which to consider this study's focus on battery and ultracapacitors, we provide a brief overview of these other VT Program research efforts.

DOE's advanced materials research is developing propulsion materials to reduce the cost and improve the durability, efficiency, and performance of not only advanced internal combustion and diesel vehicles, but also hybrid and fuel-cell-powered vehicles. Advanced materials — including metals, polymers, composites, and intermetallic compounds — are also providing lightweight, high-performance materials that by reducing vehicle weight contribute to better fuel economy and lower emissions.

DOE's research into combustion technologies and after-treatment technologies offers advanced internal combustion engines that are more efficient, using less fuel and emitting lower emissions. Use of the advanced internal combustion engine in a hybrid vehicle will further reduce its fuel use and emissions.

Identification and development of advanced petroleum- and non-petroleum-based fuels and lubricants, and studying their use in advanced internal combustion engines and their effects on the environment are additional research efforts relevant to improved hybrids. The goal is to provide vehicle users — whether hybrid or non-hybrid — with fuel options that are cost-competitive, that enable high fuel economy, deliver lower emissions, and contribute to petroleum displacement.

Advanced power electronics and electric machines for vehicle applications are additional technologies whose development will contribute to the development of hybrid and fuel cell propulsion systems with further improvements in fuel economy while complying with projected emissions and safety regulations and using fuels produced domestically. Key components for hybrid vehicles — whether fitted with a fuel cell or an advanced combustion engine — include motors, inverters/converters, sensors, control systems, and other interface

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[83] The National Academies, NRC, *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report* (2005), pp. 97–98.

electronics. These new technologies need to be compatible with high-volume manufacturing; have high reliability, efficiency, and ruggedness; offer reductions in cost, weight, and volume; and be adoptable by auto supply companies.

Development of software-based analytical tools for modeling and simulating advanced technology components, subsystems, and vehicles is another area of research that is broadly supportive of hybrid and electric vehicles. These tools enable researchers to simulate vehicle fuel economy, emissions, and performance in a realistic and cost-effective manner. The availability of accurate, flexible simulation tools to build virtual vehicles and to predict the performance of the vehicle and its components helps to assess a spectrum of advanced technologies under consideration for future vehicles. Their application also helps to guide future research directions.

Table 3.1 gives recent budget appropriations and requests for the DOE VT Program activities. The amount totals $176.1 million in FY 2008. Note that FY 2008 consolidations in the budget structure in FY 2008 of research areas having similar or congruent objectives under a single subprogram resulted in zeros for activities that were not actually eliminated; e.g., "Hybrid Electric Systems" in FY 2008 encompasses "Vehicle Systems" and "Hybrid and Electric Propulsion." Vehicle Technologies Program has announced $27.5 million for PHEV R&D in FY 2008.[84]

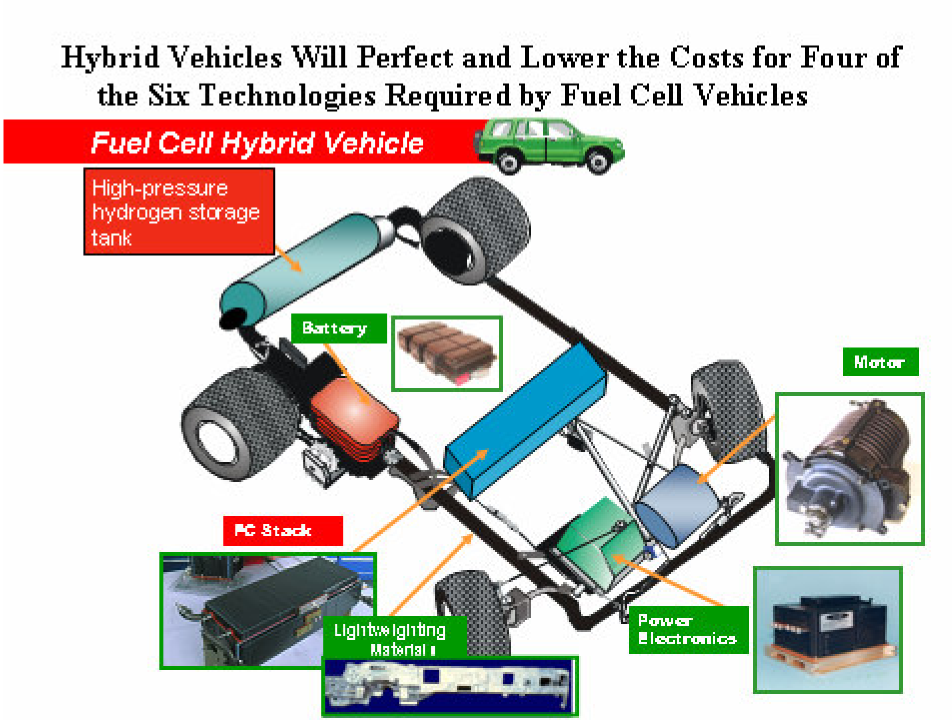
Table 3. 1 DOE Vehicle Technologies Recent Budget Appropriation and Requests

Funding ($ in thousands)			
Activity	**FY 2006 Appropriation**	**FY 2007 Request**	**FY 2008 Request**
Hybrid Electric systems	0	0	80,664
Vehicle Systems	12,720	13,315	0
Hybrid and Electric Propulsion	42,843	50,841	0
Advanced Combustion Engine R&D	40,594	46,706	33,550
Materials Technology	34,373	29,786	33,382
Fuels Technology	13,356	13,845	13,845
Technology Integration	0	0	13,697
Innovative Concepts	495	500	0
Technology Introduction	6,250	11,031	0
Technical Program Mgmt Support	2,475	0	0
Congressionally Directed Activities	24,255	0	0
Biennial Peer Reviews	990	0	0
Total	178,351	166,024	176,138

[84] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Vehicle Technologies, Fiscal Year 2008 Budget-in-Brief, available at www1.eere.energy.gov/ba/pba/pdfs/FY08_budget_brief.pdf.

Source: Fiscal Year 2008 Budget-in-Brief, U.S. Department of Energy, Energy Efficiency and Renewable Energy, Vehicle Technologies. (www1.eere.energy.gov/ba/pba/pdfs/FY08_budget_brief.pdf.)

Importantly, there are substantial synergies between DOE's research efforts that are advancing HEVs and those that are needed to advance fuel cell hybrid vehicles. Figure 3-3 shows in green four vehicle components whose development is supported by DOE VT Program research and which contribute to advances both in HEVs and fuel cell hybrid vehicles, and for which the R&D is a responsibility of the DOE Hydrogen Program. It shows in red the high-pressure hydrogen storage tank and fuel cell stack that are unique to the fuel cell hybrid vehicle.



Source: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program.

Figure 3-4. Synergy between DOE's research for HEVs and for fuel cell vehicles.

Chapter 4. Organizational Roles and Relationships

This chapter establishes the institutional context necessary for understanding how and why linkages may have developed from DOE-funded R&D to hybrid and electric cars of today. It discusses the respective roles and relationships among multiple and diverse organizations in advancing energy storage technologies from their state in the late 1970s to their state today.

4.1 The Role of DOE

In 1976, one of DOE's predecessor organizations — the Energy Research and Development Administration (ERDA) — was directed to establish a research and development program in support of electric and hybrid vehicle technologies. The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 encouraged accelerated research into, and development of, electric and hybrid vehicle technologies and established a 5-year, $160 million research, development, and demonstration project within ERDA that called for the federal development and purchase of 7,500 demonstration EVs.

When the bill establishing the Act was passed by Congress, President Gerald R. Ford vetoed it, raising the need for battery research prior to EV development:

> *It is well documented that technological breakthroughs in battery research are necessary before the electric vehicle can become a viable option. It is simply premature and wasteful for the federal government to engage in a massive demonstration program — such as that intended by the bill — before the required improvements in batteries for such vehicles are developed.* (Comments of President Gerald R. Ford to the House of Representatives on his veto of the Electric and Hybrid Vehicle Research, Development, and Demonstration Bill of 1976, Letter dated September 13, 1976)

The President's veto was overridden by the House of Representatives and by the Senate, and the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 was enacted into law.

This Act and subsequent legislation and policy actions that established the basis for DOE's programs in R&D for energy storage technologies for hybrid and electric vehicles are summarized in Table 4-1, starting with the more recent legislation.

In response to the initial legislation, DOE began three energy storage research efforts: one in electric vehicle batteries, one in batteries for utility applications, and one in basic electrochemical research. The research efforts pursued a number of different technology concepts. One effort was to improve existing battery technologies, including lead acid batteries. Other efforts were aimed at advanced concepts, including sodium sulfur and lithium iron metal sulfides.

Table 4. 1 Key Policy Actions Laying the Foundation for DOE's Hybrid and Electric Vehicle R&D Programs

2005	Energy Policy Act (EPAct) of 2005	Directed Energy Secretary to "conduct a research and development program — in consultation with other federal agencies and the private sector — on technologies related to the production, purification, distribution, storage, and use of hydrogen energy, fuel cells, and related infrastructure." Called for establishment of a program to improve technologies for the commercialization of a combination hybrid/flexible fuel vehicle or a plug-in hybrid/flexible fuel vehicle; called for acceleration of efforts to improve batteries and other rechargeable energy storage systems.
2002	Founding Agreement for FreedomCAR and Fuel Partnership.	Established partnership between DOE and USCAR to develop emission- and petroleum-free cars and light trucks.
2001	National Energy Policy (Report of the National Energy Policy Development Group)	Directed Energy Secretary to "develop next generation technology — including hydrogen." Called for income tax credits to encourage purchase of hybrid vehicles.
1993	Partnership for a New Generation of Vehicles (PNGV) established	Included goal to develop technologies that can be used to create vehicles that can achieve up to triple the fuel efficiency of today's vehicles with very low emissions, but without sacrificing affordability, performance or safety.
1992	Energy Policy Act (EPAct) of 1992	Directed Energy Secretary to "develop and implement a comprehensive program of research, development, and demonstration of fuel cells and related systems for transportation applications..." including an EV demonstration program.
1976	Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976	Created to "encourage and support accelerated research into, and development of electric and hybrid vehicle technologies..." Authorized the Hydrogen Program under the National Science Foundation. Authorized the Electric and Hybrid Vehicles Program under ERDA.

Also, there reportedly were spillovers across the application areas, with both vehicles and utilities standing to benefit from basic electrochemical research and each from advances in the other application areas.[85]

In its early period, DOE focused its vehicle energy storage research efforts on batteries for pure electric vehicles. DOE continued work on EV technology during the 1980s and into the early 1990s. The research during the early years, led by DOE, was focused primarily on validation tasks and on exploratory research. In 1990, with California's adoption of the concept of requiring introduction of zero emission vehicles, DOE's research focus on electric vehicles became stronger.

In late 1995, DOE began to provide funding of hybrid vehicle technologies. Until about 2000, DOE funded R&D related to both hybrid and purely electric vehicles, but then the focus rapidly shifted to hybrid vehicles.

In the 2000–2001 timeframe, DOE's R&D on batteries for EVs was discontinued. Resources were focused on the hybrid vehicle program. However, it should be noted that throughout the entire period extending from origination of DOE's vehicle R&D program in the mid-1970s until today, DOE continued to support cross-cutting national laboratory and university research in basic electrochemical technology. DOE also organized research at the national laboratories on the underlying science of Li-ion battery technology.[86]

In contrast when DOE's research program was largely independent of industry, the past 15 years or so has seen a close partnering of DOE with industry, with the DOE/EERE/VT Program coordinating the government's role in its current partnership with industry. According to the VT Program Office, its energy storage R&D effort is responsible for advancing the state-of-the-art and facilitating the adoption of innovative batteries for a wide range of vehicle applications.[87] It leverages all available resources, including those of automobile manufacturers, battery developers, small businesses, national laboratories, and universities, to address the technical barriers preventing the introduction of battery systems to the marketplace.[88]

4.2 The Role of Industry Consortia

In the early 1990s, the U.S. auto industry formed two industry consortia that became the focus of industry research in advanced batteries and hybrid and electric vehicles. These industry consortia also served as mechanisms that facilitated government-industry collaborative research and thereby influenced DOE research directions as described above.

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[85] Telephone interview with Mr. Ken Heitner (DOE retired), October 24, 2007, plus supporting e-mail correspondence on October 19, 2006.
[86] Telephone interview with Mr. Ken Heitner (DOE retired), October 24, 2007, plus supporting e-mail correspondence from Mr. Heitner on October 19, 2006.
[87] FCVT Multi-year Program Plan, 2003, Section 4.3, p. 4–29.
[88] Ibid, p. 4–30.

4.2.1 U.S. Advanced Battery Consortium (USABC)

The primary industry consortium for battery research was the USABC, formed in 1991, as a consortium of the automobile manufacturers — Chrysler, Ford, and General Motors, the Electric Power Research Institute (EPRI), various battery development firms, the national laboratories, and universities. Its mission is to develop electrochemical energy storage technologies that support commercialization of fuel cell, hybrid, and electric vehicles.[89]

DOE signed an agreement with the USABC shortly after its formation for a joint program, based on a realization that the issue of energy storage was sufficiently challenging that government and industry researchers would make more progress in a collaborative effort than alone. DOE brought the technical resources of its laboratories, expertise in problem solving, and program management to the joint DOE/USABC development program.[90] Industry brought technical and management resources, as well as market knowledge. DOE research managers saw this partnership between DOE and the USABC as marking a turning point in DOE's energy storage program towards goals that made more sense and were in tune with industry.[91]

In conjunction with its joint program with USABC, and in tune with USABC's first-round program, DOE initiated nickel metal hydride battery development oriented toward applications in the shorter term. At the same time, DOE continued longer term research on battery technologies such as lithium metal polymer, lithium ion polymer, sodium sulfur, and lithium ion disulfide technologies, considered promising for further applications.

Under DOE's and USABC's cooperative agreement, DOE provides up to 50 percent of the USABC budget. DOE funding is used to fund research, and the industry share of costs is split among the automakers and the USABC contractors. The government share is for research, and industry is responsible for costs of manufacturing advanced batteries.[92]

Using DOE funding, the USABC awards pre-competitive energy storage technology development contracts to firms with the objective of using contractor-government partnership to help achieve goals. For example, in December 2006, it awarded a $15 million contract to A123Systems to develop Li-iron phosphate battery technology for HEV applications. It allocates funding through a process that entails the issuance of a Request for Proposals (RFP).

As of March 2007, the USABC gave as its objectives for high-energy and high-power energy storage technologies and models, to continue its focus on understanding and addressing the following factors:[93]

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[89] USABC press release announcing a contract to A123Systems, December 6, 2006, articulated the consortium's mission.
[90] Ibid.
[91] Based on interviews with DOE research managers Tien Duong, David Howell, and Ken Heitner (retired).
[92] The National Academies, *Effectiveness of the United States Advanced Battery Consortium as a Government-Industry Partnership* (1998), p. 21.
[93] Further information about the USABC can be found at its Web site, www.uscar.org/guest/view_team.php?teams_id=12.

- Continue development of high-power battery technologies to reduce cost to $20/kW and extend life to 15 years.
- Develop battery technology to support electric, hybrid and fuel cell vehicles.
- Develop ultracapacitor technology for hybrid electric vehicle applications.
- Conduct benchmarking activities for both high power and high energy batteries and ultracapacitors to validate technologies.
- Publish technical goals and associated test procedures to guide the development of electrochemical energy storage systems.

4.2.2 U.S. Council for Automotive Research (USCAR)

Soon after its formation, the USABC in 1992 became affiliated with another industry consortium: USCAR. This second consortium was formed as an umbrella organization of Chrysler,[94] Ford Motor Company, and General Motors Corporation for the stated purpose of strengthening the technology base of the U.S. auto industry. Thus its technology focus was broader than that of the USABC and was overlapping with it. Over the years, USCAR has developed partnerships with a variety of other collaborative organizations concerned with automotive technologies, among them the following:

- U.S. Advanced Battery Consortium (USABC)
- Automotive Composites Consortium (ACC)
- Environmental Research Consortium (ERC)
- Vehicle Recycling Partnership (VRP)
- Low Emissions Technologies R&D Partnership (LEP)
- Occupant Safety Research Partnership (OSRP)
- U.S. Automotive Materials Partnership (USAMP)
- Partnership for a New Generation of Vehicles (PNGV)
- Supercomputer Automotive Applications Partnership
- Electrical Wiring Component Applications Partnership (EWCAP)
- FreedomCAR (Cooperative Automotive Research)
- FreedomCAR & Fuel Partnership
- U.S. Alliance for Technology and Engineering for Automotive Manufacturing (US A-TEAM)

USCAR's organizational structure includes an Executive Leadership Group and nine Technical Leadership Councils (TLCs). The TLCs manage the USCAR's collaborative research and development portfolio, establish strategic objectives, and oversee teams that are the basic research units of USCAR.

4.3 The Role of Government-Industry Partnerships

Two major government/industry partnerships were formed to advance automotive technologies. The first — the Partnership for a New Generation of Vehicles (PNGV) was created by the Clinton Administration in 1993, and the second — FreedomCAR and Fuel

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[94] Chrysler has changed organizationally over the period since the consortia was formed, first participating as Chrysler Corporation, later as DaimlerChrysler, and now as Chrysler LLC.

Partnership — was created by the Bush Administration in 2002, at which time the former was terminated.

4.3.1 Partnership for a New Generation of Vehicles

In 1993–94, the federal government, in conjunction with its agreement with USABC, partnered with industry in a broad, government-led program called the PNGV.

The PNGV was a cooperative R&D partnership between USCAR and eight federal agencies, five of which are shown in Figure 4-1. The three agencies with leading roles were DOE, Department of Commerce (DOC), and National Science Foundation (NSF); other involved agencies were the Departments of Defense, Interior, and Transportation, the Environmental Protection Agency, and the National Aeronautics and Space Administration. In addition, several government laboratories had participants on the technical teams.[95]

The purpose of PNGV was to create a prototype super-efficient car through a three-stage approach. The long-run goal was that by 2004, the member automakers would produce a prototype car (not necessarily marketed to the public) that would achieve approximately 80 miles per gallon; would cost no more in real terms to own and drive than a conventional auto of 1994; would maintain performance, size, and utility; and would meet or exceed safety and emission requirements of comparable mid-size conventional family sedans of 1994. An important milestone of PNGV was to identify by the end of 1997 the most promising technologies, including those for energy storage. At the same time, the industry partners were conducting in-house proprietary R&D programs.[96]

Funding for the PNGV entailed cost sharing by government and industry, intended to approximate 50–50 shares. The government share was to be applied to projects with relatively high risk, and the industry share was to fund product development and commercialization.[97] Figure 4-1 shows federal funding by agency from FY 1995 through FY 1999. The total federal funding over the period totaled approximately $1.25 billion — averaging about $250 million per year — about half of which was provided by DOE.

Industry participants reported positive effects from the PNGV. They reported that the partnership was a more efficient approach to achieving objectives than the regulatory approach, that the PNGV enabled the carmakers to stretch their short-term research focus, that they faced competition from European and Asian carmakers who were receiving support from their governments to develop new automotive technologies,[98] and that market forces alone would not cause them to set a goal as ambitious as the 80 mpg goal of the PNGV.[99]

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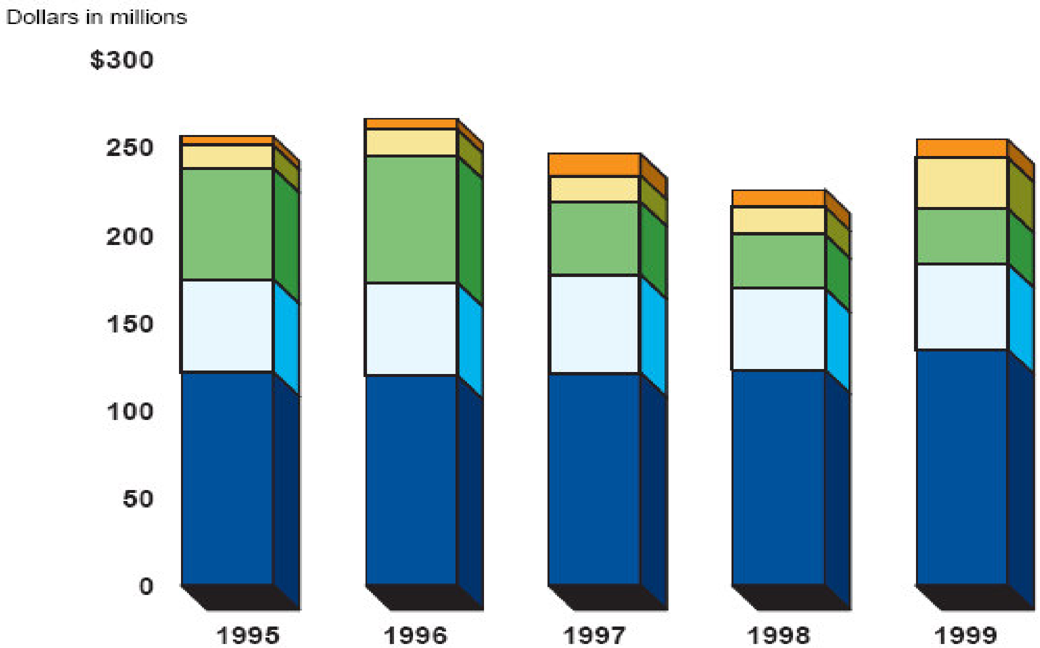
[95] Fred Sissine, Congressional Report Service, Report for Congress, "The Partnership for a New Generation of Vehicles (PNGV)," pp. 96–191 SPR, February 28, 1996.

[96] National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Fourth Report, 1998.

[97] National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Fourth Report, 1998.

[98] The Analytic Sciences Corporation (TASC), 1995, reported on government support of auto research in the European Union (EU) through the European Council for Automotive Research and Development (EUCAR), and



	1995	1996	1997	1998	1999
DOT	5.0	5.5	12.5	10.0	10.5
EPA	13.0	14.9	15.0	15.6	29.0
DOC	63.3	72.5	41.4	30.6	31.1
NSF	53.0	53.0	56.0	46.6	49.3
DOE	121.2	119.6	121.0	122.7	134.1

Source: U.S. General Accounting Agency (2000), p. 14.

Figure 4- 1. Estimated PNGV funding allocations by federal agency, FY 1995–99

Administration arguments for a federal role included issues surrounding importation of petroleum and emissions, importance of the auto industry, to the U.S. economy, and the need for support for pre-competitive technology development as a U.S. competitiveness strategy.[100]

An Operational Steering Group of representatives from the various government and industry partners coordinated PNGV policy. The Department of Commerce chaired the government Steering Group. Energy storage technology R&D was overseen by the USCAR/PNGV Electrochemical Energy Storage (EES) Technical Team.

DOE played a major role in PNGV and received the largest share of appropriated PNGV funding, as shown in Figure 4-2. One reason for DOE's leadership role in PNGV was that for the preceding years, it had run an electric- and hybrid-vehicle R&D program. Another lay in

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in Japan through the Ministry of International Trade and Industry (MITI) as the focus of industry-government cooperation. (Ibid.)

[99] Ibid.

[100] Ibid.

the technical expertise, facilities, and resources of the national laboratories, useful for achieving PNGV goals. Furthermore, the national laboratories had a number of existing Cooperative Research and Development Agreements (CRADAs) with the USCAR consortium under which joint industry/national laboratory research was performed.

4.3.2 FreedomCAR and Fuel Partnership[101]

In 2002, the FreedomCAR and Fuel Partnership initiative replaced PNGV. Like the PNGV, FreedomCAR was aimed at increasing fuel efficiency of automobiles, but the FreedomCAR initiative extended the time frame by another 10 years and focused research on hydrogen fuel cells in contrast to the PNGV's later focus on hybrid vehicles.[102] The FreedomCAR and Fuel Partnership seeks the development of emission- and petroleum-free cars and light trucks that do not limit freedom of mobility and vehicle choice. The program continued R&D on electrical energy storage systems, including batteries and power capacitors. Questions have been raised regarding the effect the changed government focus on hydrogen and fuel cell vehicle technologies may have on advanced hybrid technologies that are closer to commercialization.[103]

Members of the FreedomCAR and Fuel Partnership include DOE; the USCAR partners of Chrysler, Ford, and General Motors; and five major energy companies — BP Amoco, ChevronTexaco, ConocoPhillips, ExxonMobil, and Shell. In addition, the partnership includes the national laboratories, automotive supplier companies, and universities. The government's role in the partnership is coordinated by DOE/EERE/VT Program.

The FreedomCAR and Fuel Partnership started with a presidential commitment to request $1.7 billion over the 5 year period from FY04 to FY08. The FY05 appropriation was about $310 million and the FY06 presidential budget request was about $360 million.[104]

4.4 National Laboratories

Multiple DOE national laboratories have roles in energy storage R&D. Under FreedomCAR and Fuel Partnership, five national laboratories — Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Idaho National Laboratory (INL), Lawrence Berkeley National Laboratory (LBNL), and Sandia National Laboratory (SNL) — are conducting applied battery research activities. Their focus includes work on second-generation lithium-ion battery systems, and investigation of performance and failure mechanisms affecting individual components of the battery systems. LBL also is conducting

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[101] The Hydrogen Fuel Initiative announced by President Bush in 2003 was intended to complement the FreedomCAR initiative. It focused on hydrogen fuel and infrastructure. (Brent D. Yacobucci, CRS Report RS21442, February 7, 2006, Hydrogen and Fuel Cell Vehicle R&D: FreedomCAR and President's Hydrogen Fuel Initiative, p. 1.)

[102] Ibid, pp. 1–2.

[103] Ibid, p. 6.

[104] The National Academies, National Research Council, "Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report (2005)", p. 73.

long-term battery research, with a focus on promising electrode materials and electrolytes and advanced material diagnostics.

In addition to the five laboratories listed above, the National Renewable Energy Laboratory (NREL) plays an important role in energy storage R&D. It is conducting thermal modeling, characterization, and control studies to increase understanding and control of thermal abuse and to achieve more uniform temperature control over the battery module, which is necessary for longer battery life.[105]

More detail about each of these DOE national laboratories, together with the centers or divisions or programs within which energy storage R&D activities are concentrated or coordinated, is provided in Appendix B, Section B.1. The roles of each in the area of energy storage for hybrid and electric vehicles are described in Appendix B.

4.5 Automotive Manufacturer and Supplier Companies

Through the USCAR and USABC consortia, Chrysler, Ford Research Laboratories, and General Motors have been major collaborators with DOE and its laboratories under PNGV and FreedomCAR in the development of energy storage technologies. In addition to the automotive manufacturers and energy companies, a number of energy storage developers and suppliers have collaborated in the R&D sponsored by PNGV and FreedomCAR and coordinated by the consortia. Companies that have collaborated either as energy storage team members or as subcontractors to USABC or to the national laboratories include but are not limited to those listed in Table 4-2.

Table 4. 2 Examples of Firms Participating in Government/Industry Partnerships and Consortia

Firms Participating in Partnerships and Consortia*	
Chrysler	Johnson Controls
Ford	Johnson Controls-SAFT Joint Venture
General Motors	LG Chem
Advanced Engineering Solutions	Maxwell Technologies
AVESTOR	Millennium Cell
BAE Systems	NESSCAP
Cobasys	Optima
Compact Power	Plastic Technology Partners
Delphi	PolyStor
Energy Conversion Devices	SAFT
ElectraStor	Sentech Corp
Electro Energy	Texaco-Ovonic
Hydro Quebec	VARTA
GNB Industrial Power	Ener1, Inc.

*Note: this is not an all-inclusive listing.

[105] The National Academies, National Research Council, "Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report (2005)", p. 73.

4.6 Universities

Universities participate in a variety of ways in DOE-sponsored energy storage R&D. One category of involvement is through university-run or university-affiliated national laboratories; e.g., University of California-Berkeley and LBNL. Another category is university research funded by national laboratories; e.g., SNL has had studies carried out at the University of Maryland for the DOE Energy Storage Systems Program;[106] NREL's energy storage project team has worked with researchers from the University of Toledo, Ohio, on an award-winning paper; LBL's BATT Program has worked with researchers at Brigham Young University, State University of New York at Binghamton, Columbia University, North Carolina State University, Michigan State University, Clemson University, University of Utah, University of Texas-Austin, MIT, State University of New York at Stony Brook, and University of Michigan, Ann Arbor. Other national laboratory-funded universities contributing to VT Program's energy storage R&D include the Illinois Institute of Technology, the University of Puerto Rico, and Clemson University, to name only a few.[107]

University collaborators in the FreedomCAR and Fuel Partnership include Graduate Automotive Technology Education (GATE) Centers of Excellence to foster the training of engineers skilled in advanced automotive technologies. For example, the Pennsylvania State University's GATE Center is focused on high power energy storage systems. Among the GATE Centers are the following: University of Alabama at Birmingham, University of Illinois at Urbana-Champaign, Virginia Polytechnic Institute and State University, Virginia State University, Ohio State University, University of California-Davis, Pennsylvania State University, University of Tennessee, and University of Michigan-Dearborn.

4.7 Other Organizations: Societies, Institutes, Advisory Panels, and Foreign Competitors

Heretofore, this chapter has focused on organizations that have played a direct role in the development of energy storage technologies for HEVs, PHEVs, and EVs with funding from DOE. Here, to provide a more complete picture, we look briefly at other organizations that have also played important, though different, roles in the development and commercialization of energy storage technologies for HEVs, PHEVs, and EVs. Other influential organizations include associations, institutes, advisory panels, and foreign competitors.

4.7.1 Societies and Institutes

The Society of Automotive Engineers (SAE) issues test procedures and technical standards and recommended practices including those pertaining to energy storage, which are used by industry. The national laboratories provide significant input to this process. SAE also disseminates information on the most advanced technologies in hybrid vehicle technologies to the automotive community through symposia, books, electronic products and databases, technical papers, and reports.

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[106] Sandia report, SAND2005-0372.
[107] FCVT 2005 Annual Report.

The Electrochemical Society and other technical societies and associations in the field also help to disseminate research findings on advanced batteries and ultracapacitors by publishing research results in their journals. For example, the Electrochemical Society includes DOE presentations, paper, and abstracts on battery and ultracapacitor research in its meetings, journal, and at its Web site.[108]

EPRI, an independent, nonprofit center for research in the public interest on electricity generation, delivery, and use, has also played a role in vehicle energy storage research. For example, EPRI entered into a three-year collaborative agreement with ANL to conduct detailed analysis of PHEVs, focused on assessing the commercial feasibility of the technology.

4.7.2 Advisory Panels and Oversight Organizations

Advisory, oversight, and assessment organizations have played a unique role in the development, commercialization, and assessment of energy storage technologies for HEVs, PHEVs, and EVs.

The Office of Technology Assessment (OTA) — closed in 1995 — provided oversight of DOE's vehicles program. For example, a 1995 OTA report, commented that DOE had underestimated the length of time it would take to achieve its research goals and to commercialize resulting technologies.[109] It also noted in its annual report to Congress that battery energy storage capacity continued to be a challenge.

The National Academies' National Research Council (NRC) has provided annual program reviews of the PNGV beginning in 1994 and continuing through 2001. And, in 2005, NRC provided a similar review of FreedomCAR. The external reviews provided insight as to the perceived feasibility of the programs' energy storage R&D goals and progress against goals. Highlights from these NRC reviews as they relate to energy storage technologies for electric and hybrid vehicles are provided in Appendix B, Section B.3.

4.7.3 Foreign Collaborators and Competitors

Foreign collaborators and competitors have also conditioned development and commercialization by U.S. firms of energy storage technologies for HEVs, PHEVs, and EVs.

Foreign competitors have affected U.S. manufacturers in multiple ways. First, as previously noted, Japan's effort to launch its own intensive program to fast-track hybrid technologies may have been, in part, stimulated by PNGV, which generally was not open to Japanese firms, although barriers appear to have lessened in later years.

Second, Toyota adopted a different commercialization strategy than U.S. firms, reportedly entering the HEV market as a loss-leader, willing initially to sell HEVs at a loss. In contrast, U.S. manufacturers reportedly were not willing to market HEVs until they estimated they

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[108] Available, for example, from Randy B. Wright, David K. Jamison, and Tien Q. Duong, is "FreedomCAR Testing of Selected Commercial Ultracapacitors," 204th Meeting of The Electrochemical Society, Inc., 2003.
[109] U.S. Congress, Office of Technology Assessment, *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, OTA-ETI-638, Sept. 1995, p. 47.

could do so at a profit. This difference in marketing philosophy was reportedly the reason in large part for Toyota's early lead in marketing HEVs in the United States.[110]

In addition, and as noted previously, foreign competitors — particularly the Japanese — were often observed during the 1990s to have a broad competitive edge in manufacturing, resulting in a rising share of U.S. inventions being commercialized offshore. As noted earlier, this development stimulated the U.S. Congress to establish partnership programs aimed at improving the competitive abilities of U.S. manufacturers.[111]

Licensing and cross-licensing of energy storage intellectual property is another way in which foreign companies have interfaced with U.S. companies. An early instance of cross-licensing resulted from settlement of a patent infringement case brought by the U.S. innovator of NiMH batteries against Japanese companies Panasonic and its parent company. (This infringement case is discussed further in Chapter 5.) As another example, Ford and Toyota entered into a licensing exchange agreement in 2004.[112]

As an example of a collaborative research effort with foreign competitors, there reportedly has been a sharing of energy storage R&D results between the DOE and the Korea Automotive Research Institute (KATECH), which is supported by the Korean Ministry of Commerce, Industry and Energy. [113] KATECH is Korea's national laboratory for automotive research.[114]

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110 Telephone interview with Mr. Gary Henriksen, ANL, March 5, 2007.
111 For example, the Technology Competitiveness Act of 1988 established the Manufacturing Extension Partnership (MEP) program.
112 Todd Zaun, "Ford to Use Toyota's Hybrid Technology," *The New York Times*, Archives, March 10, 2004.
113 FCVT 2005 Annual Report.
114 More about KATECH can be found on its Web site, www.katech.re.kr/eng/index.asp.

Chapter 5. Key Linkages Identified by Experts

This chapter documents linkages that were identified through interviews with knowledgeable experts close to DOE's vehicle research program, national laboratory research, and also to the broader energy storage community. In separate interviews, multiple research managers from DOE headquarters and the national laboratories all focused on the same several companies and company families, identifying them as particularly significant in providing key linkages.

Figure 5-1 summarizes the identified connections. They include battery purchases by auto companies from battery suppliers; licensing among battery suppliers; patent infringement settlement; payment of recoupment royalties to DOE; extensive cross-citing of patents; company funding by USABC/DOE; publishing and licensing by the national laboratories of their research results and sharing of their test methods and data, joint research with companies, and funding of university research; program initiatives provided by the private-public partnership programs; and DOE's leadership and funding roles.

5.1 Linkages through ECD Ovonics and its Strategic Partners and Licensees

A key linkage identified by the DOE research managers who were interviewed[115] centered on Energy Conversion Devices, Inc. (also known as ECD Ovonics), its subsidiary, Ovonic Battery Company, and three joint venture companies formed between ECD Ovonics and the following entities: General Motors Corporation, Chevron Texaco Technology Ventures, and Chevron Technology Ventures LLC. For purpose of the study, this collection of companies is referred to as the ECD Ovonics group, and comprises the companies listed in Table 5-1. An overview of their interrelationships and accomplishments is provided below. An important linkage of DOE to downstream battery application for EVs and HEVs is provided through this company group. [Specifics from the interviews with DOE research managers are provided in Appendix C, Section C.1]

5.1.1 About the ECD Ovonics Group and its Links to EV and HEV Batteries

Energy Conversion Devices, Inc. (ECD)116 (NASDAQ: ENER). Headquartered in Rochester Hills, MI, the company has three core businesses, each conducted through a variety of strategic alliances: (1) Energy Storage, (2) Energy Generation, and (3) Information Technologies — the first listed being the focus of this study. ECD's energy storage work is performed by its subsidiary, Ovonic Battery Company.

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[115] In separate interviews, multiple research managers from DOE headquarters and the national laboratories all focused on the same several companies and company families, identifying them as particularly significant in providing key linkages.
[116] More information about ECD Ovonics may be found at www.ovonic.com

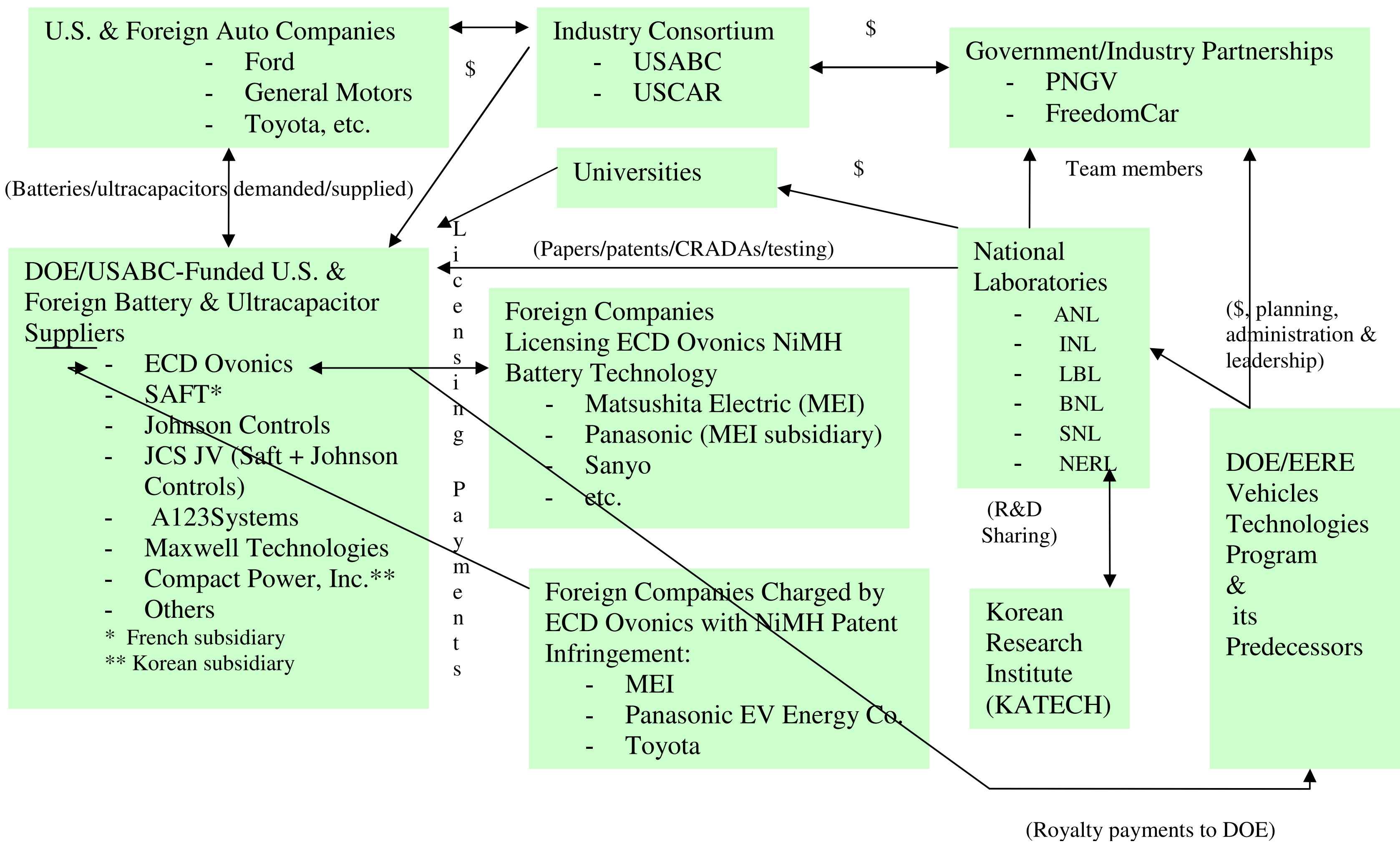

Figure 5-1. Linkages identified by experts

Table 5. 1 Core Group with Key Linkages between DOE-Supported R&D and Commercialized Batteries for HEVs

Referenced Group	Companies in Group	Company Origins
Group Centered on ECD Ovonics	Energy Conversion Devices, Inc. (ECD)	Also known as ECD Ovonics, established by Stanford Ovshinsky
	Ovonic Battery Company, Inc.	Subsidiary of ECD
	GM Ovonics	JV of General Motors and Ovonic Battery Company
	Texaco Ovonic Battery Systems LLC	JV of Chevron Texaco Technology Ventures and Ovonic Battery Company
	Cobasys LLC	JV of Chevron and Ovonic Battery Company

Ovonic Battery Company, Inc. In 1992, this subsidiary of ECD was awarded its first contract by USABC, with part of the funding provided by DOE. The contract was to develop and demonstrate NiMH batteries for EV applications. In conjunction with this effort, GM produced its all-electric vehicle, EV-1, powered with Ovonic's NiMH batteries — the first EV to achieve a range of over 220 miles on a single charge. In 1996, an Ovonic advanced NiMH battery pack was used in a Solectria EV race car, Sunrise, which set a world record of over 373 miles on a single charge.

PNGV then provided funding to the company for development of a NiMH battery for use in HEVs. With this funding, Ovonic Battery Company successfully demonstrated specially designed NiMH batteries with high power and extended cycle life for use in HEVs. Subsequently, the automotive industry used these batteries to demonstrate hybrid electric vehicles; the technology was licensed from ECD Ovonics by a number of battery suppliers, including major Japanese battery companies, and NiMH batteries based on the company's technology became incorporated into existing and upcoming HEV production models. Ovonic NiMH batteries are now beginning to be used in heavy-duty transit vehicles such as a prototype school bus used in California.[117]

GM Ovonics. This joint venture between GM and Ovonic Battery Co., a subsidiary of ECD, was formed in 1994 to manufacture and commercialize high-efficiency NiMH automobile batteries. The goal was to fully commercialize and expand applications of NiMH batteries.

In 2000, Texaco announced its plan to acquire GM's share of the joint venture with Ovonic Battery Co, rename it, and expand commercial applications to a broad range of energy markets. In announcing plans for the acquisition, Texaco's Senior Vice President William Wicker noted an expectation that the demand for electric and hybrid vehicles would grow significantly, and called the time right for extension of the Ovonic NiMH technology to the

[117] See "Case Studies" at the ECD Ovonics Web site, www.ovonic.com/eb_case_studies.cfm.

entire automotive market.[118] At the time of the announcement, GM's Vice Chairman Harry Pearche noted the importance of addressing the critical issue of battery cost — which required both high-volume applications and further technical development.[119] He went on to say, "General Motors, ECD, and Ovonic led the industry in the initial commercialization and technology development for advanced vehicle batteries,"[120] and noted that the GM Ovonic's Kettering, Ohio, plant was the first and only facility in the United States dedicated exclusively to the production of NiMH batteries for EVs. He indicated that GM expected that Texaco Ovonic would be its supplier for NiMH batteries.[121]

Texaco Ovonic Battery Systems LLC was formed as a 50-50 joint venture company between a unit of Chevron Texaco Technology Ventures and Ovonic Battery Company, Inc, when Texaco acquired GM's 60 percent share of the existing joint venture with Energy Conversion Devices, in which Texaco already held a 20 percent interest.

According to the President of Texaco Ovonic Battery Systems, "The development program currently underway at Texaco Ovonic Battery Systems is based on the fundamental inventions and pioneering work in NiMH batteries by Stanford R. Ovshinsky, President and CEO of ECD, and Ovonic Battery Company that provides the enabling technology."[122] Texaco's Senior Vice President William Wicker stated, "ECD and Ovonic developed breakthrough advanced NiMH battery technology and General Motors has brought it to the production stage."[123]

Building on the enabling technology of Ovonic Battery Company, Texaco Ovonic Battery Systems further developed the NiMH battery for HEVs through three phases of a contract that included support from DOE. Phase 1 focused on improving the NiMH battery. Phase 2 emphasized durability and manufacturability concepts. Phase 3, launched in 2002, with a $5.2 million, two-year cost-sharing contract under the sponsorship of DOE's FreedomCAR initiative, continued development work on the company's proprietary liquid-cooled 12V monoblock NiMH battery technology for HEVs, focused on full HEV battery systems meeting performance and production cost targets. The stated project goal was delivery of complete 25kW battery pack systems, including thermal management, control electronics, and a battery management system. At the time of the Phase 3 award, the president of Texaco Ovonic Battery Systems noted, "This important work, based upon our proprietary NiMH battery

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118 Autoparts Report, October 19, 2000, "Texaco to Acquire Majority of GM Ovonic Battery Joint Venture," Gale Group.
119 Ibid.
120 Autoparts Report, October 19, 2000, "Texaco to Acquire Majority of GM Ovonic Battery Joint Venture," Gale Group.
121 Ibid.
122 ChevronTexaco Press Release, "Texaco Ovonic Battery Systems Announces Award of Contract under the FreedomCAR Initiative," issued by Texaco Ovonic Battery Systems LLC, August 31, 2002. (www.chevron.com/news/press/2002/2002-07-31_1.asp.)
123 Ibid.

technology, will help accelerate the commercialization of hybrid technologies for a broad range of transportation applications."[124]

Cobasys LLC. Cobasys, a joint venture between Chevron Technology Ventures LLC, a subsidiary of Chevron Corporation, and Energy Conversion Devices, Inc. (which owns 50 percent of Cobasys) was founded to continue development and commercialization of ECD Ovonics' proprietary Ovonic NiMH battery technology. Cobasys designs, manufactures, integrates, and supplies NiMH batteries for HEVs and EVs, and also for stationary market applications. Through its 50 percent equity interest, ECD Ovonics provided Cobasys with a competitive advantage by giving it the exclusive worldwide right to sell NiMH batteries for HEVs and other uses, and the exclusive right to sublicense proprietary Ovonic NiMH technology in the market segments it serves. The company is headquartered in Orion, Michigan, and has its manufacturing facility in Springboro, Ohio.[125]

Cobasys' brand name for its integrated battery system for HEVs — including system design, battery modules, packaging, wiring, thermal management, battery management electronics, control algorithms, interface to applications, assembly, engineering support, integrating service and project management — is NiMHax®. According to company information, its batteries will last over 200,000 miles under a partial charge/discharge regime when used in HEV applications. The company markets its NiMHax® for a variety of applications, ranging from small HEVs to SUVs to large bus HEVs.

5.1.2 Licensing Agreements Showing Linkages through the ECD Ovonics Group to Global Producers of NiMH Batteries for HEVs

Ovonic Battery Company has extensively licensed its patents for proprietary NiMH battery technology, providing the royalty-bearing, nonexclusive right to make, use, and sell NiMH batteries for vehicles and, in addition, for consumer, nonpropulsion applications. In descriptions of its work, ECD Ovonics states, "Every major NiMH battery manufacturer is using licensed Ovonic technology."[126] Table 5-2 provides a partial list of ECD Ovonics' battery's licensees. To the extent that Ovonic's battery research was partially funded by DOE — as the evidence indicates — Table 5-2 suggests a far reaching impact of the DOE-supported NiMH battery R&D on the worldwide battery industry. Particularly significant among the licensees listed in Table 5-2 are Matsushita Electric, parent of Panasonic, and Sanyo Electric Co., which became major OEM suppliers of the current generation of NiMH batteries in HEVs.

[124] Joint Press Release between Chevron and Texaco Ovonic Battery Systems LLC, July 31, 2002. (www.chevron.com/news/press/Release/?id=2002-07-31a)
[125] More about Cobasys may be found at www.ovonic.com and www.cobasys.com.
[126] This statement was found on the ECD Ovonics web site in its overview of the work of the Ovonic Materials Divisions, under a highlighted sidebar, "ovonics@work" (www.ovonic.com/eb_ba_omd_overview.cfm)

Table 5. 2 Partial List of Licensees of Ovonic Battery Co.'s NiMH Battery Technology

BYD Battery	Nan Ya Plastic
Canon	SAFT
Daido Steel	Samsung
Energizer	SANIK Battery Co., Ltd.
Furukawa	Sanoh
GP Batteries	Sanyo Electric Co.
Guangdong Shida Battery	Shenzhen High Power Tech Co.
Harding Energy	Sovlux Battery
Hitachi Maxell	TMK Power Industries
Hunan Corun	Toshiba Battery
Hyundai	TWD Battery
Intellect Battery Co. Ltd.	Union Suppo Battery Company
Japan Storage	USABC
KAN Battery	Walsin
L&K Battery Technology Company LTD	Yuasa
Lexel Battery	
Linghao Battery (H.K.) Co., Ltd.	
Matsushita Electric Industrial Co. (parent of Panasonic)	

Source: ECD Ovonics.

5.1.3 Royalty Payments Showing Linkage from DOE Funding to ECD Ovonics' NiMH Battery and to HEVs

DOE was directed by Congress to have a recoupment policy for four of its programs, one of which was the Electric Vehicle Advanced Battery Development Program. DOE's recoupment policy issued April 8, 1998, states "The policy of DOE is to recoup, where appropriate, some or all of the Department's investments in its technology RD&D programs, where the results of such investments give rise to successfully commercialized technologies."[127] In accordance with this policy, the 1992 cost-sharing subcontract of USABC with ECD Ovonics contained a recoupment provision that required the company to repay DOE 7.5 percent of net royalties per year, up to the amount of the funding DOE provided.

[127] This account of DOE's recoupment draws from letters from ECD Ovonics to DOE's staff in the Office of Advanced Automotive Technology and to a contract specialist in its Operations Division at Argonne National Laboratory, dated July 9, 2002; DOE internal memoranda; Certification for Intellectual Property Licenses provided by ECD Ovonics to DOE; and related documents made available by DOE/EERE to this study.

Documents pertaining to royalty payments made under the recoupment agreement state that ECD Ovonics developed NiMH batteries for electric vehicles under a subcontract totaling $27.2 million, of which DOE provided $13.6 million, USABC provided $5.4 million, and ECD Ovonics provided $8.2 million. A royalty payment to DOE arose from the licensing and incorporation of ECD Ovonics' technology in a NiMH battery provided by Sanyo for the Ford Hybrid Escape and the Honda Accord. As a result, ECD Ovonics has made royalty payments to DOE/EERE that have been returned to the U.S. Treasury. This payment of royalties provides a clear linkage from DOE-funded R&D to batteries in commercialized HEVs.

5.1.4 Patent Infringement Case and Settlement Showing Linkage of ECD Ovonics' NiMH Battery to Japanese Battery Companies

A patent infringement case was filed in 2002 by ECD Ovonics against Matsushita Electric Industrial Co. (MEI), Panasonic EV Energy Co (PEVE), and Toyota Motor Corporation over Ovonic NiMH patented battery technology reportedly used in the Toyota Prius.[128] A counterclaim was filed in turn by the parties charged.

ECD Ovonics announced a settlement in July 2004, under which Cobasys received $20 million for licenses granted to MEI/PEVE and Toyota. Furthermore, the settlement called for Cobasys to receive royalties through 2013 on certain NiMH batteries sold by MEI/PEVE in North America. COBASYS and PEVE agreed to cross-license each other for current and future patents to avoid possible future litigation. COBASYS and PEVE agreed to a technical cooperation agreement to advance the state-of-the-art of NiMH batteries for HEVs. COBASYS and PEVE also established a joint development program under which they agreed to collaborate on the development of next-generation high performance NiMH batteries for HEVs filed through 2014. Under terms of the agreement, details of the settlement are confidential.[129, 130]

In 2005, Cobasys and PEVE announced an extension to their agreement for cooperation, with Cobasys granting additional royalty-bearing license rights to PEVE. The expanded rights permit PEVE to solicit and sell NiMH battery products for certain North American transportation applications in return for royalties to Cobasys on PEVE's North American sales of NiMH battery products through 2014. In addition, under terms of the expanded agreement, Cobasys and PEVE agreed to continue to cross-license each other for current and future patents through 2014, and to maintain their technical cooperation to advance the NiMH battery products and continue their joint development for the next generation of NiMH battery products for HEVs.

The parties also agreed to evaluate the feasibility of assembling PEVE battery packs at Cobasys' Springboro, Ohio, manufacturing facility. According to Cobasys President and CEO, Thomas Neslage, "We believe this agreement will complement our core business

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[128] Brion D. Tanous, Merriman Curhan Ford & Co., "Initiating Coverage of Next-Generation Energy Pioneer with Buy Rating," September 21, 2004.
[129] U.S. Securities and Exchange Commission, Form 8-K, July 7, 2004.
[130] ECD Ovonics Press Release, "ECD Ovonics Announces Settlement in Patent Infringement Dispute; Cobasys and Panasonic EV Energy to Cooperate in the Development of Next-Generation State-of-the-Art Nickel Metal Hydride Batteries," July 7, 2004.

strategies, provide additional revenue, and enhance our progress toward achieving full manufacturing capacity at our Springboro, Ohio, plant."[131] The licensing and technology development agreements of Cobasys with MEI/PEVE ended costly litigation, and provided revenue and potential future commercial advantages to Cobasys.[132]

Given that DOE partially funded Ovonic's R&D on the subject NiMH batteries, the patent infringement charges brought against the Japanese companies and the subsequent payments to Cobasys and cross-licensing agreements suggests additional paths of influence — beyond the direct licensing path — from DOE-funded battery R&D into the international battery market for HEVs. This additional path connects DOE-funded R&D to Toyota's HEVs.

5.1.5 Published Documents Showing Linkages of DOE-Funded R&D to HEVs through the ECD Ovonics Group

A news story released by Cobasys in December 2006 announced that it has been chosen to provide its NiMHax® battery system for GM's 2007 Saturn Aura Green Line Hybrid Mid-Size Sedan scheduled for release to consumers in the spring of 2007. The Aura Green Line is said to deliver a 25 percent fuel economic improvement over the base Aura XE model.[133] The news story noted that Cobasys' NiMH battery also powers GM's Saturn VUE Green Line model, a mid-size crossover SUV. The VUE, a mild hybrid, was being touted as "the most affordable S.U.V. hybrid."[134]

In addition, it was announced that Cobasys has been awarded one of two contracts by GM to compete for supplying Li-ion plug-in batteries for use in the Saturn VUE Green Line PHEV SUV. In announcing the awards, GM's director of hybrid energy storage systems stated, "Thanks to critical relationships with the U.S. government, collaborative research with Ford and DaimlerChrysler under the United States Advanced Battery Consortium (USABC), significant progress has been made in battery research."[135]

Cobasys is working in partnership with A123Systems on the plug-in battery effort. They are in competition with Johnson Controls-SAFT Advanced Power Solutions, LLC, a joint venture which received the second award. According to GM's director of hybrid energy storage systems, "the companies will be challenged to prove the durability, reliability, and potential cost at mass volumes of their technology."[136] Reportedly, the two test batteries — one from each contract and differing in their chemistries — will be evaluated in prototype Saturn VUE

[131] Industry News, "Cobasys and Panasonic EV Energy Extend Cooperation," July 19, 2005 (www.powerpulse.net/story.php?storyID=13593).
[132] Assessing the actual impacts of the agreements on the involved parties goes beyond the scope of this study.
[133] Cobasys Press Release, "Cobasys Providing Battery System for Saturn Aura Green Line Hybrid Sedan," December 4, 2006 (www.ovonic.com/PDFs/PressReleases/cobasys_saturn-aura-green-line.pdf.)
[134] Bradley Berman, "Behind the Wheel, Saturn VUE Green Line and Mercury Mariner: Hybrids, Mild or Seasoned, from the Motor City," *The New York Times*, November 19, 2006.
[135] PRNewswire, "GM Awards Lithium Ion Battery Development Contracts," January 4, 2007. (www.euroinvestor.co.u,/News).
[136] PRNewswire, "GM Awards Lithium Ion Battery Development Contracts," January 4, 2007.

Green Line plug-in hybrids beginning late in 2007.[137] According to GM, it may seek additional agreements in its effort to find battery solutions to meet its PHEV targets.[138]

Thus, the DOE-funded ECD Ovonics/Cobasys battery technology is directly traceable to EVs, HEVs, and, potentially, PHEVs of U.S. auto producers. In addition, it is traceable indirectly through licensing and possible patent infringement to NiMH batteries of Panasonic and Sanyo that are found in many of the currently available HEVs.

5.1.6 Patent Trees Showing Linkages from DOE-funding of the ECD Ovonics Group to NiMH Batteries

While there were 60 patents awarded to the ECD Ovonics/Ovonic Battery Company family, the patent filings did not acknowledge an interest by DOE. Therefore, we looked to DOE's database of patents, which identifies patents that DOE has at least in part funded, to identify those linked to back to DOE. Only three patents issued to Ovonic Battery Company, Inc., were found in the DOE database: #5,258,242 filed in 1993 and issued in 1993; #5,348,822 filed in 1992 and issued in 1994, and #5,506,069 filed in 1994 and issued in 1996. Of these, the most often cited is #5,348,822, and it is examined here in more detail.

Patent #5,348,822, "Chemically and compositionally modified solid solution disordered multiphase nickel hydroxide positive electrode for alkaline rechargeable electrochemical cells," cited 10 previous patents and, in turn, was cited by 30 later, referencing patents. The referencing patents include several that include "hybrid electric vehicle" in their titles, including several assigned to Ovonic Battery Company, one filed in 1997 and issued in 2001, as well as one assigned to Matsushita Electric Industrial Company filed in 1998 and issued in 2000.

Figure 5-2 shows the first-generation forward citations, in five-year time increments, for Ovonic Battery Company's Patent #5,348,822, from its time of issue through mid-2007. Table 5-3 lists the 9 assignee companies of the 30 first-generation patents that cited the patent. The table identifies the citing patents by number, title, and year of issue. It also gives a color-code used for each company's patent displayed in Figure 5-2.

The second-generation patent tree is shown in Figure 5-3. That is, it adds to the first-generation of patents that cited the target patent directly, those patents that cited those first-generation-citing patents. Due to its length, the second-generation tabular listing is provided in Appendix C, Section C.2.

There are more than 50 additional assignee companies of patents in the second-generation group, including Johnson Research & Development Company and SAFT (both color coded in green), companies that were identified by experts as also providing important linkages from DOE research to commercialized batteries used in hybrid and electric vehicles. (See Subsection 5.2.1 for more about Johnson and SAFT). In addition, this second-generation list

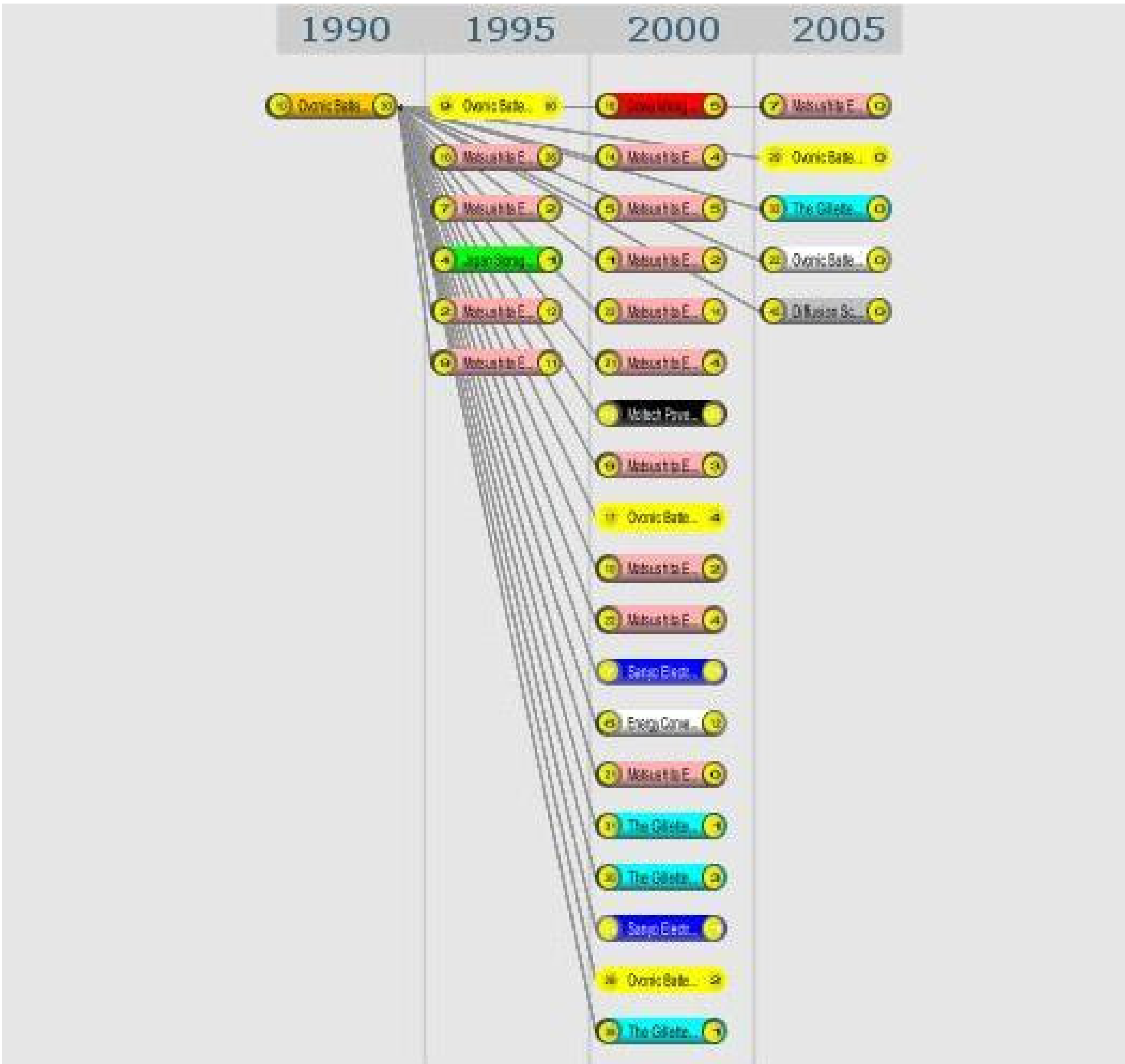
[137] Ibid.
[138] Ibid.

adds Toyota, Sony, and Sumitomo — among other Japanese firms — to Matsushita and Sanyo.

By the third generation the total number of assignee firms has risen to several hundred, and includes A123Systems, another company identified by DOE experts as providing important linkages to next-generation HEVs and PHEVs. (See Subsection 5.3.1 for more about A123Systems.) The third-generation patent tree is not shown because it is too complex and densely populated to decipher in print size. Importantly, the list now includes General Motors, Mitsubishi, and Honda Motor Co., in addition to the two major NiMH battery producers, Matsushita and Sanyo.

The patent trees provide graphical representations of forward patenting leading from the Ovonic Battery Company's patent #5,348,822 to downstream commercializers of batteries and vehicles. To the extent that the later patents are dependent on the initial patent, later patents in the tree represent developments in knowledge that are dependent, at least in part, on DOE funding.

Chapter 6, which takes a broader approach to patent citation analysis, provides additional information about the influence of patents from the ECD Ovonics Group — as well as other organizations — on battery/ultracapacitor patents for HEV/PHEV/EV applications.



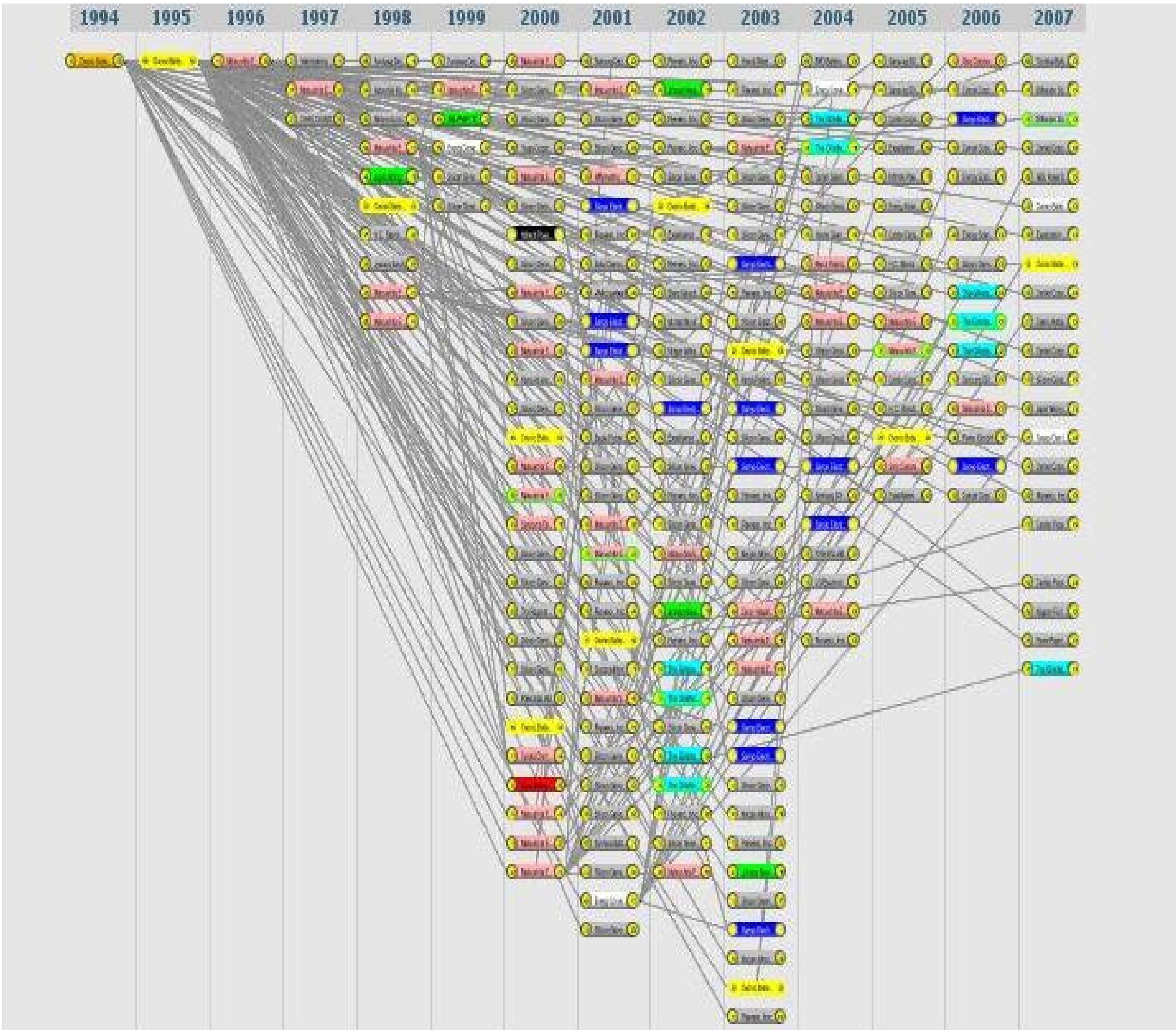
Note: This display of forward patent citations was generated using Delphion's Citation Link. The referenced Ovonic patent is shown in orange. For companies citing this patent, see the color-code in Column 2 of Table 5.3. The Delphion-generated patent displays when copied and enlarged tend to lack visual sharpness; hence Table 5.3 is provided to clarify the linkages.

Figure 5-2. First-generation patent tree for US5348822, issued to Ovonic Battery Company in 1994

Table 5. 3 Nine Assignees of 30 First-Generation Patents Citing Ovonic Patent #5,348,822

Companies whose Patents Directly Referenced #5,348,822	Color-Code in Fig. 5-2	Patents Citing #5,348,822	Citing Patent's Title
Matsushita Electric Industrial Co., Ltd.	Pink	6,858,347	▪ Paste type positive electrode for alkaline storage battery and nickel-metal hydride storage battery (2005)
		6,284,215	▪ Manufacturing method of active materials for the positive electrode in alkaline storage batteries (2001)
		6,261,720	▪ Positive electrode active materials for alkaline storage batteries (2001)
		6,255,019	▪ Cathode active material for alkaline storage battery and cathode using the same (2001)
		6,156,456	▪ Positive electrode active material for alkaline storage battery (2000)
		6,153,334	▪ Active materials for the positive electrode in alkaline storage battery and manufacturing method (2000)
		6,129,902	▪ Manufacturing method of active materials for the positive electrode in alkaline storage batteries (2000)
		6,074,785	▪ Nickel/metal hydride storage battery (2000)
		6,066,416	▪ Nickel hydroxide positive electrode active material having a surface layer containing a solid solution nickel hydroxide with manganese incorporated therein (2000)
		6,013,390	▪ Alkaline storage battery (2000)
		5,773,169	▪ Active material and positive electrode for alkaline storage battery (1998)
		5,744,259	▪ Nickel positive electrode for alkaline storage battery and sealed nickel-metal hydride storage battery (1998)
		5,656,396	▪ Alkaline storage battery (1997)
		5,571,636	▪ Nickel positive electrode for alkaline storage battery and sealed nickel-hydrogen storage battery using nickel positive electrode (1996)
Sanyo Electric Co., Ltd.	Blue	6,479,189	▪ Sealed alkaline storage battery with a manganese containing NIOH electrode (2002)
		6,203,945	▪ Nickel hydroxide active material for use in alkaline storage cell and manufacturing method of the same (2001)

Japan Storage Battery Co., Ltd.	Green	5,814,108	▪ Method for manufacturing nickel-metal-hydride battery (1998)
Energy Conversion Devices, Inc.	White	6,177,213	▪ Composite positive electrode material and method for making same (2001)
Ovonic Battery Company, Inc.	White Or Yellow	7,261,970 6,837,321 6,557,655 6,330,925 5,411,592	▪ Nickel metal hydride battery design (2007) ▪ Hybrid electric vehicle incorporating an integrated propulsion system (2005) ▪ Hybrid electric vehicle (2003) ▪ Hybrid electric vehicle incorporating an integrated propulsion system (2001) ▪ Apparatus for deposition of thin-film, solid state batteries (1995)
Diffusion Science, Inc.	Grey	7,198,867	▪ Electrochemical generation, storage, and reaction of hydrogen and oxygen (2007)
Moltech Power Systems, Inc.	Black	6,020,088	▪ Gamma NiOH nickel electrodes (2000)
The Gillette Company	Aqua	7,081,319 6,740,451 6,492,062 6,489,056	▪ Preparation of nickel oxyhydroxide (2006) ▪ Gold additive for a cathode including nickel oxyhydroxide for an alkaline battery (2004) ▪ Primary alkaline battery including nickel oxyhydroxide (2002) ▪ Battery including a hydrogen-absorbing cathode material (2002)
Dowa Mining Co., Ltd.	Red	6,077,496	▪ Positive electrode active material for nonaqueous secondary cells and a process for producing said active material (2000)



Note: This display of forward patent citations was generated using Delphion's Citation Link. As previously noted, the Delphion-generated patent displays when copied and enlarged tend to lack visual sharpness. The figure is intended to portray the complexity of this diffusion process. The second-generation tabular listing of citing companies is provided in Appendix C, Section C.2.

Figure 5-3. Second-generation patent tree for US5348822, issued to Ovonic Battery Company in 1994

5.2 Linkages from DOE-Supported R&D through SAFT, Johnson Controls, and the Johnson Controls-SAFT (JCS) Joint Venture

Another company group highlighted by the interviews as providing key linkages from DOE-supported R&D in energy storage technologies to batteries for HEVs, PHEVs, and EVs is a group centered on SAFT America, Johnson Controls, and a joint venture formed by the two companies, referenced here as JCS Joint Venture. The interviewees emphasized both early linkage from DOE through SAFT to EV demonstration fleets of the 1990s, and prospective linkages from DOE through JCS to batteries for next-generation HEVs and PHEVs.

5.2.1 About Johnson Controls, SAFT, and JCS Joint Venture

Johnson Controls, founded in 1885, and headquartered in Milwaukee, Wisconsin, is reportedly the world's largest supplier of automotive batteries.[139] Furthermore, more recently, it has been a research leader in new lithium-ion batteries for hybrid cars. Johnson Controls also produces the PowerWatch™ System which monitors the state of the battery in HEVs.[140]

In 2004, Johnson Controls received from the USABC (with funding from DOE) an 18-month contract supporting R&D of advanced Li-ion battery technology. [141]

SAFT (Société des Accumulateurs Fixes et de Traction) specializes in the design and manufacture of advanced technology batteries for industry, including transportation applications. SAFT, a French-based company, has a strong U.S. presence, with locations in Cockeysville, Maryland; Valdese, North Carolina; Valdosta, Georgia; and West Palm Beach, Florida.

SAFT was funded by DOE to develop NiMH batteries. It has developed a wide range of battery technologies, including NiMH, nickel-cadmium (Ni-Cd), and Li-ion, for a variety of market segments, including automotive applications for HEVs, PHEVs, and EVs. SAFT's STM series high energy Ni-Cd batteries are reportedly used in approximately 10,000 EVs in Europe. Their applications include all-electric buses, trucks, compact cars, and minivans. SAFT series STH Ni-Cd batteries are used in HEVs.[142]

The joint venture between Johnson Controls and SAFT — called Johnson Controls-SAFT Advanced Power Solutions or JCS — was launched in January 2006. In August 2006, the USABC awarded JCS a two-year contract with funding provided by DOE through the FreedomCAR and Fuel Partnership to continue development work on advanced Li-ion battery technology for HEV, PHEV, and EV applications.

The focus of the R&D under the contract is on accelerating Li-ion technology development by improving battery power in low temperatures and creating solutions that reduce battery system costs needed to drive the technology to commercial viability.[143] According to Alan Mumby, Johnson Controls' Vice President and General Manager of the company's hybrid battery business, as well as leader of the JCS Joint Venture, "This program enabled by the USABC

[139] Johnson Controls Press Release, "Johnson Controls to Acquire Fiamm's Automotive Battery Business," October 26, 2006, http://www.johnsoncontrols.com.
[140] More about Johnson Controls may be found at the company's Web site, www.johnsoncontrols.com.
[141] Johnson Controls Press Release, "Johnson Controls-Saft Joint Venture Targets Development of Advanced, Lithium-Ion Batteries for Hybrid-Electric Vehicles," August 14, 2006, www.johnsoncontrols.com.
[142] More about SAFT may be found at the company's Web site, www.saftbatteries.com.
[143] Ibid and Johnson Controls Press Release, "Johnson Controls-Saft Joint Venture Awarded Program for Lithium-Ion Batteries," September 6, 2006 (www.johnsoncontrols.com).

contract positions the JCS joint venture as the leading manufacturer of lithium-ion batteries for the next generation of alternative powertrain vehicles."[144]

As noted previously, JCS was one of two groups provided a contract by General Motors to design and test Li-ion batteries for use in the Saturn VUE Green Line plug-in hybrid SUV.[145] (As explained in Section 5.1.5, the other agreement was signed with Cobasys, which is working in partnership with A123Systems to develop Li-ion battery technology.)

5.2.2 DOE Funding of Foreign-owned Companies

Commenting on USABC/DOE contracting with SAFT, EERE program staff explained that a United States-based subsidiary of a foreign owned company is allowed to participate in USABC/DOE-funded research. Noting SAFT's battery manufacturing plants in the United States, the staff member stated:

> *We would want at least half the contract work to be done in the United States. The company signs a letter of intent under the Energy Policy Act that encourages them, if successful, to increase manufacturing jobs in the United States. They understand when they enter into the contract that they are to increase manufacturing jobs in the United States.* (Mr. David Howell, Interview, Washington, DC, October 19, 2006)

Another former EERE research manager emphasized the important role played by SAFT, in conjunction with ECD Ovonics, in developing NiMH batteries for the Daimler Chrysler and General Motors demonstration fleets of EVs in the 1990s.[146]

5.3 Linkages from DOE-Supported R&D through A123Systems

The DOE/EERE persons interviewed noted an additional prospective linkage from DOE to next-generation HEVs and PHEVs — that linkage being through A123Systems. Moreover, recent developments suggest that A123Systems may be positioned to play a significant role in next-generation Li-ion batteries for hybrid vehicles.

A123Systems, founded in 2001, has its headquarters in Watertown, Massachusetts, where it has R&D and pilot production facilities. It has manufacturing plants and subcontractor facilities in the United States, China, Korea, and Taiwan. Major shareholders of the company include Motorola, Qualcomm, Sequoia Capital, North Bridge, YankeeTek, MIT, and OnPoint Technologies, a strategic private equity firm funded by the U.S. Army.

According to A123Systems' publicly available information, its batteries use nanoscale materials that are inexpensive, nontoxic, and stable in electrochemical systems to offer very

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[144] Johnson Controls Press Release, "Johnson Controls-Saft Joint Venture Awarded Program for Lithium-Ion Batteries," September 6, 2006 (www.johnsoncontrols.com).
[145] "Johnson Controls unit lands contract for plug-in hybrid battery," Wisconsin Technology Network, January 4, 2007.
[146] Interview with Mr. Ken Heitner, EERE (retired), October 19, 2006, and follow-on telephone discussion, October 24, 2006.

high levels of power, safety, and lifetimes. The company was able to commercialize the lithium battery initially not for vehicles but for power tools.[147] Beyond power tools, the batteries have potential applications in robotics, home appliances, electric drive systems, stationary power, load balancing, specialized military equipment, and medical devices.[148]

On December 8, 2006, the USABC announced an award of a $15 million, 36-month contract to A123Systems to support development of the Li-ion technology for HEVs. According to the Executive Director of USCAR, Don Walkowicz, “The program (represented by the contract between USABC and A123Systems) is essential to advance both near- and long-term goals for hybrid-electric vehicle transportation.”[149] The focus was on developing high-power, abuse-tolerant, long-lived, and cost-effective battery technology. An A123Systems battery is projected to be 80 percent lighter than batteries used in current HEVs and to offer superior life and durability.[150] The contract award was the first from USABC to A123Systems,[151] the previous DOE support to the company having been from DOE’s Small Business Innovation Research (SBIR) program.

In February 6, 2006, A123Systems announced that it had raised $30 million in a third round of private equity funding, which brought its total equity funding to $62 million — this in addition to the USABC/ DOE contract funding and earlier DOE SBIR grants. According to the company, it will use its capital infusion, among other things, to increase manufacturing capacity and to accelerate development of batteries for HEVs.[152]

These developments preceded A123Systems’ announcement on January 3, 2007, that it had formed a partnership with Cobasys to supply General Motors (GM) with batteries for its prototype Saturn VUE Green Line plug-in hybrid SUV. In announcing the partnership, Mr. David Vieau, CEO and President of A123Systems, said, “This partnership will provide the market with game changing performance to further accelerate the adoption of hybrid electric vehicles.”[153] According to the announcement, A123Systems’ role will be to manufacture and supply its nanophosphate Li-ion cells, while Cobasys’ role will be to provide technical assistance and expertise for the design and development of the battery system, including packaging, thermal management, wiring, electronics, and control algorithms, and to help meet the integration needs of customers.[154]

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[147] The company is supplying batteries to Black & Decker for heavy-duty portable power tools, (www.a123systems.com)

[148] Interview with Mr. David Howell, October 19, 2006, DOE Forrestal Building, Washington, DC.

[149] USCAR Press Release, “USABC Awards $15 Million Battery Technology Development Contract to A123Systems,” December 8, 2006.

[150] A123Systems Press Release, “A123Systems Receives $30 Million Investment to Increase Production and Expand its Battery Product Portfolio into New Markets, including Hybrid Electric Vehicles,” February 6, 2006.

[151] USCAR Press Release, “USABC Awards $15 Million Battery Technology Development Contract to A123Systems,” Dec. 8, 2006.

[152] A123Systems Press Release, “A123Systems Receives $30 Million Investment to Increase Production and Expand its Battery Product Portfolio into New Markets, including Hybrid Electric Vehicles,” February 6, 2006.

[153] A123Systems Press Release, “Cobasys and A123Systems Announce Partnership to Develop Lithium Ion Hybrid Electric Vehicle Battery Systems,” January 3, 2007.

[154] A123Systems Press Release, “Cobasys and A123Systems Announce Partnership to Develop Lithium Ion Hybrid Electric Vehicle Battery Systems,” January 3, 2007.

5.4 Linkages through DOE-Developed Test Results and Test Manuals

DOE/EERE and national laboratory program staff, a battery developer, and a National Research Council Committee all noted the importance of test results and test manuals to downstream commercialization of batteries.

5.4.1 National Laboratory Battery Testing

DOE/EERE program staff emphasized that the national laboratories — particularly ANL, INL, and SNL — have through their battery testing provided linkages from DOE to downstream commercial development of batteries. They explained three aspects of the testing that each have a unique downstream effect.

First, the national laboratories test the performance of batteries developed by companies under contract delivery to USABC. The results are said to influence the decisions of the USABC to pursue or not to pursue further development of a given battery technology and the decisions of auto manufacturers to consider the batteries for future use in their vehicles. The results also provide feedback to the battery developers, informing them about their performance data.

Second, ANL provides benchmark testing of batteries developed globally by battery developers. These test results provide independent, consistent testing of many different batteries produced, generally in prototype, by many battery developers. The benchmark testing allows USABC to stay abreast of battery innovations worldwide and to compare the performance attributes of the various available batteries. According to ANL's Battery Test Facility Web site, it has tested more than 3,000 cells, configured into multi-cell modules and full-size batteries, representing 13 types of battery systems provided by 18 battery developers.[155]

Third, in order to carry out their battery tests, ANL, INL, and SNL develop test protocols, often in collaboration with USABC. Over time, ANL and INL have developed a series of manuals setting forth testing protocols for different batteries, and updated them as necessary to keep pace with growing experience and new technical results.

5.4.2 Adoption of Test Practices by the Society of Automotive Engineering (SAE)

The USABC references these manuals developed by the national laboratories, and SAE adopts these protocols as Recommended Practices for the automotive industry. As an example of how the test manuals developed by the national laboratories have served as the basis for establishing recommended practices or standards for industry, see highlighted below the scope of the SAE standard, *Electric Vehicle Battery Abuse Testing*, document number J2464, issued by the SAE Hybrid Committee, March 1999. The SAE standard is derived from a similar document originally developed by the USABC, which in turn was derived from DOE laboratory test protocols. [A listing of DOE laboratory test protocols for hybrid electric energy storage systems is provided in Appendix B, Section B.2.]

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155 "Battery Testing and Analysis," Argonne Battery Research and Development, www.cmt.anl.gov/Science_and_Technology/Batteries/default.shtml.

Prior to the development by the government laboratories of test protocols, and their adoption by the SAE as standards, each automobile manufacturer had its individual programs for testing batteries, and there was no independent, consistent testing that could provide comparable results across batteries of different types, from different firms and different countries. [For more from the interviews regarding the importance of testing and test results to commercialization, see Appendix C, Subsection C.1.2]

Scope of SAE J2464: This SAE Recommended Practice is intended as a guide toward standard practice and is subject to change to keep pace with experience and technical advances. It describes a body of tests which may be used as needed for abuse testing of electric or hybrid electric vehicle batteries to determine the response of such batteries to conditions or events which are beyond their normal operating range. **This document [SAE J2464] is derived from a similar document originally developed by the U.S. Advanced Battery Consortium.** (Bolding added) Source: SAE website www.sae.org/technical/standards/J2464_199903.

5.5 Linkages through DOE National Laboratory R&D

The DOE research managers also noted that the national laboratories have contributed to the knowledge base through their research programs, and that companies and other organizations have drawn from this knowledge base in developing and commercializing energy storage technologies. National laboratory knowledge outputs are reflected in the publications, presentations and patents of staff members, as well as those sponsored by the laboratories and conducted by others. Transference of knowledge also occurs through informal networking and collaboration of researchers, which, though important, may not produce recorded outputs.

For illustrative purpose, we examine modes of linkages to downstream commercialization of HEVs, PHEVs, and EVs as seen through the eyes of national laboratory research managers[156] for just two of the national laboratories: ANL and LBNL.[157]

5.5.1 ANL's Key Modes of Linkage through R&D

In addition to testing, the manager of ANL's Battery Technology Department identified two other modes of linkage as particularly noteworthy: (1) collaborative battery research with battery developers through CRADAs, and (2) dissemination of ANL's research results through publications, patents, and licensing. The ANL manager noted that the laboratory's influence

[156] One expert from each laboratory was selected based on the collective recommendation of the four DOE/EERE research managers initially interviewed, but not all responded. Others may have offered additional or different insights.

[157] The national laboratories are represented in the patent citation analysis of Chapter 6, and each of those described as most prominent in energy storage research is described in Appendix B.

will come mainly in the next generation of HEVs and PHEVs, which will be powered by advanced Li-ion battery technology now under development.[158]

Two examples of CRADA work with battery developers were identified as significant despite the fact that neither provided a clear path to commercialized innovation. These are briefly summarized to emphasize the point made by several DOE researchers that finding out what is not the best way to go and ruling out technical approaches are also valuable contributions to progress.[159] One example was joint research with SAFT America on EV battery technology in the early 1990s. In conjunction with this research effort, ANL reportedly invented Li-ion sulfate battery technology. A spin-off of this research was later used by DOE for other applications. Meanwhile, the auto manufacturers decided that they did not want a high-temperature battery, such as that provided by the Li-ion sulfate technology, and ANL ruled it out for further development around 1994. Another example was a CRADA with 3M and HydroQuebec in the 1994–98 timeframe to develop medium-temperature battery technology. This effort ended when the research found life-cycle limitations and other technical problems. Thus, while the results of neither of these CRADAs found their way directly into HEVs, much was learned from the effort that informed further research directions.

ANL's battery research manager identified a group of publications and patents from ANL's Battery Technology Department as particularly important to downstream progress.[160] These are listed in Appendix C, Section C.1.3. Although most of the ANL patents in the list are too recently filed to allow for much referencing by other patents, their licensing provides a potential path to market. ANL recently licensed its cathode patents included in the group to NanoeXa, a California-based nanotechnology clean energy company founded in 2005. In addition, ANL licensed its battery electrolyte additives to NanoeXa, and also supplied A123Systems with electrolyte additives for evaluation. The Battery Technology Department is reportedly in discussions with the ANL Tech Transfer Office to initiate further licensing of its intellectual property.

The licensing agreements are supportive of a recently signed agreement between ANL and NanoeXa and Decktron, a South Korean lithium battery company acquired by NanoeXa. Under the agreement, the company is to develop and transfer into commercial use next-generation rechargeable lithium battery technologies from ANL's Battery Technology Department.[161] This effort is expected to be facilitated by the fact that Dectron has battery manufacturing operations equipped with scalable production facilities.[162] According to the CEO of NanoeXa:

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[158] Interview with Mr. Gary Henriksen, Manager, Battery Technology Department, Chemical Engineering Division, ANL's Transportation Technology R&D Center, March 5, 2007.
[159] Ibid.
[160] Post-interview material provided by Mr. Gary Henriksen, March 5 and 6, 2007.
[161] "NanoeXa and Argonne National Laboratory to Commercialize Next Generation Lithium Battery Technologies," Green Car Congress, September 27, 2006, (www.greencarcongress.com/2006/09/nanoexa_and_arg.html); and Argonne Press Release, September 27, 2006.
[162] "NanoeXa Lithium Ion Batteries," The Energy Blog, September 30, 2006 (http://thefraserdomain.typepad.com/energy2006/09/nanoexa_lithium.html).

One of the primary goals of Argonne's battery technology is to dramatically improve lithium battery safety. Argonne's R&D expertise in developing lithium battery materials as well as their deep relationships with the world's automotive makers will create a powerful opportunity for our company.
(Michael Pak, CEO of NanoeXa)[163]

ANL's battery research manager also identified additional noteworthy patents attributed to ANL researchers in the category of lithium batteries, as shown in Appendix C, Section C.1.3. The list includes many patent applications not yet granted, which attests to the young profile of this patent portfolio and the challenge in adequately capturing linkages from much of the laboratory's recent R&D in lithium batteries to downstream commercialization. This finding is consistent with the description in Appendix B of ANL's emphasis on lithium batteries for next-generation HEVs and PHEVs. It appears that ANL is building an intellectual property portfolio and putting licensing agreements in place to help develop the energy storage technologies needed to realize the next-generation hybrids.

5.5.2 LBNL's Key Modes of Linkage through R&D

John Newman, a senior research scientist, a highly cited author in LBNL's Materials Sciences Division, and leader of BERC — the electrochemical research arm of FreedomCAR, provided his views about the linkage of LBL's outputs to downstream commercialization.[164] He placed prime emphasis on LBNL's publications as providing a path of linkage, and called personal networking as the next most important path.

Emphasizing the academic environment of LBNL and the indistinct lines between the University of California and LBNL, Newman reported seeing benefit from collaborative research to the professors who perform research, to the students who may assist and who have the advantage of being taught by those at the forefront of research, and also to the companies that participate in the research and exploit the knowledge.

Regarding networking and collaborative activities, he also noted the transference of knowledge downstream through consulting of faculty members with industry. He gave as an example his own consulting work with Johnson Controls, a company that, together with its partner, SAFT, has been asked by GM to design plug-in Li-ion batteries for a Saturn hybrid vehicle.

LBNL's role in the early development of batteries for EVs also should be noted. In 1992, LBNL formed a CRADA with USABC to develop lithium/polymer cells for EVs in a $260 million, 4-year project. This effort was stimulated by adoption of the California Air Resources Board of its zero-emissions mandates. At the time, USABC saw great promise in Lithium/polymer batteries.[165]

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[163] As quoted in "NanoeXa and Argonne National Laboratory to Commercialize Next Generation Lithium Battery Technologies," see above.
[164] Interview with Professor John Newman, Researcher in the Materials Sciences Division, Department of Chemical Engineering, University of California, LBNL, March 9, 2007.
[165] Jeffery Kahn, "LBL to develop batteries for electric vehicles," July 19, 1992, www.lbl.gov/Science-Articles/Archive/battery-consortium.html.

5.6 Linkages through Other Companies

A review of documents revealed additional companies funded by DOE to develop energy storage systems for HEVs and PHEVs beyond those already identified. Two of these — Maxwell Technologies, Inc. and Compact Power, Inc. — are discussed here.

5.6.1 A Potential Linkage through Maxwell Technologies, Inc.

Maxwell Technologies, Inc. (NASDAQ: MXWL) is the leading manufacturer of ultracapacitors in the United States. In addition to applications in transportation, Maxwell also provides power solutions for applications in consumer and industrial electronics and telecommunications. The company has facilities in San Diego, California and in Rossen, Switzerland.[166]

On March 9, 2005, Maxwell announced in a press release that the USABC had selected it to develop ultracapacitor-based energy storage modules for passenger vehicles, and under FreedomCAR it would receive more than $3 million in matching funds for a two-year contract to develop a compact, low-cost, high-performance, 48-volt ultracapacitor-based electrical energy storage module. The terms of the contract called for Maxwell to deliver fully integrated multicell modules for testing by DOE's SNL and INL against rigorous auto industry standards for energy capacity, pulse power, abuse tolerance, and calendar life and cycle life. According to the company, the independent third-party testing will supplement and validate the performance and reliability data that the company has been generating internally and through customer beta testing.[167]

On announcing funding from USABC, Dr. Richard Balanson, Maxwell's President and CEO, related that the company sees sponsorship by USABC as an opportunity to further accelerate acceptance of ultracapacitors as a standard building block for energy storage and power delivery solutions. Dr. Balanson stated, "This opportunity with USABC to develop an auto-specific module will enable us to strengthen our credentials as a supplier of mainstream energy storage systems."[168] About the significance of the company's technology, Richard Smith, Maxwell's Executive Vice President for Strategic Business Development, said, "The MC2600 cell and BMOD2600-48 module are major stepping stones to penetrating the transportation and industrial markets by providing the advanced, low-cost, energy storage and power delivery technology that these applications require."[169, 170]

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[166] "About Maxwell," www.maxwell.com/about-maxwell/facilities-manufacturing.asp.
[167] Ibid.
[168] Maxwell Technologies Press Release, "U.S. Advanced Battery Consortium Selects Maxwell Technologies to Develop Ultracapacitor-based Energy Storage Module for Autos," March 9, 2005.
[169] Maxwell Technologies news release, "BMOD2600-48 BOOSTCAP® Ultracapacitor Module" (undated), http://www.globalspec.com/FeaturedProducts/Detail/MaxwellTechnologies/BMOD260048_BOOSTCAP_Ultracapacitor_Module.
[170] In November 2006, Maxwell Technologies, Inc., introduced a compact, fully integrated, 125 volt BOOSTCAP® ultracapacitor module that provided an easy-to-integrate building block for scalable energy storage and power delivery solutions for heavy hybrid and electric vehicles (bus, truck, and electric rail vehicles) and heavy-duty industrial applications. The module delivers up to 10 times the power and longevity of batteries, and is said to perform reliably through one million or more deep charge/discharge cycles, which equates to more

5.6.2 A Potential Linkage through a U.S. Subsidiary of a Korean Company, Compact Power, Inc. (CPI)

CPI, headquartered in Troy, Michigan, is a subsidiary of LG Chem, a Korean-based chemical company and one of the world's largest producers of Li-ion batteries for automotive hybrid electric vehicles and non-automotive markets.

CPI has received five contracts from USABC since 2002, all aimed at broadening the knowledge base of Li-ion batteries for passenger cars and moving them closer to market. On signing its first development contract with USABC, the president of LG Chem noted that the company was the first Asian company to sign such a contract with USABC, and noted that its contract with USABC put it in an advantageous position for securing the Big Three Automakers as potential customers.[171]

The most recent contract — for 18 months, and, at $6.3 million, the largest received — was announced October 16, 2006. The contract is focused on cell development issues including improving life cycle and calendar life, cold-cranking power, abuse tolerance, low-temperature performance, module development including thermal issues, battery module electronics, cell interconnections, and abuse testing. According to the company's CEO, "The development work behind this contract allows us the opportunity to continue enhancing the acceptance of lithium-ion as a viable battery technology for hybrid-electric vehicles. As one of the primary developers of lithium-ion batteries for North American hybrid electric vehicles, we are ideally positioned to add value to USABC's work."[172]

5.6.3 A Likely Understatement of Linkages through DOE/USABC-Funded Companies

There are additional companies that have received funding for energy storage R&D from USABC/DOE, as well as publishing and licensing opportunities through the national laboratories that have not been covered here. Thus, this coverage likely understates the linkages from DOE-funded R&D to downstream commercialization of hybrid and electric vehicles.

5.6.4 A Possible Shift in Drivers of Company Linkages over the Period Covered

The identified company linkages that occurred early in the period covered appear to reflect the early leadership of U.S. companies in battery innovations. The more recent identified linkages may reflect a growing concern of U.S. companies that they need to ensure a ready network of suppliers for batteries for HEVs and PHEVs that are not under control of large automotive manufacturers headquartered outside the United States. For example, officials at Ford Motor Company have said they now want to procure more parts from their own factories or from American parts makers.[173]

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than 15 years of operational life—this according to Richard Smith, Maxwell's executive VP for strategic business development. (Ibid.)

[171] "LG Building Lithium-Ion Hybrid Batteries for Detroit," August 23, 2004. (www.greencarcongress.com/2004/08/lg_building_lit.html).

[172] Compact Power, Inc. (CPI) Press Release, "Compact Power, Inc. Awarded Lithium-Ion Battery Technology Development Contract by USABC," October 16, 2006. (www.compactpower.com).

[173] James Brooke, "In the Hybrid's Wake, Trying to Catch Up," *The New York Times*, October 20, 2005.

Chapter 6. Linkages Identified by Patent Citation Analysis

Whereas Chapter 5 featured linkages identified by expert opinion, assessed by interview, and supplemented by additional techniques, this chapter provides an overview of linkages at the organization level and at the patent level identified by patent citation analysis alone. Organizational-level results show the extent of DOE's connections to the patents of different organizations active in HEV/PHEV/EV battery and ultracapacitor technology. Patent-level results reveal specific DOE patents that have been particularly influential. The patent-level results also reveal patents from other organizations that have built extensively on DOE-funded patents. This analysis is built on methodology described in more detail in Chapter 2 and Appendix A.

6.1 Organizational-Level Results

In assessing the extent of DOE's connections to the patents of other organizations active in HEV, PHEV, and EV battery and ultracapacitor technology, it is important to provide context. Hence, at the organizational level, DOE's connections are compared to those of other leading organizations active in the same technology area.

6.1.1 Number of Battery Patents

DOE-funded patents represent the second largest portfolio in the battery/ultracapacitor set. DOE's 71 funded patents found in the HEV/PHEV/EV set are assigned to a variety of organizations, notably General Electric, University of Chicago (which operates ANL), University of California (which operates LBNL), and Maxwell Technologies. These 71 patents describe various technologies within the HEV/PHEV/EV set as identified by applying the filtering process described in Chapter 2 and elaborated in Appendix A.

How significant are the 71 DOE-funded patents relative to those of other leading organizations, and specifically to those of Japanese companies? Figure 6-1 shows the organizations with the largest number of patents in the battery/ultracapacitor set tied directly to HEVs/PHEVs/EVs. DOE's 71 is exceeded only by Matsushita Electric's 99; Matsushita Electric heads the list. Next after DOE is NEC with 60 patents, followed by Honda with 50 patents. Of the seven organizations with the highest number of patents in the battery/ultracapacitor set tied directly to HEVs/PHEVs/EVs, all were Japanese except for DOE.

The Matsushita patents included in Figure 6-1 describe a variety of technologies, including Li-ion and NiMH batteries, and double layer capacitors. The patent sets of other Japanese companies in the list are more focused. For example, the patents of NEC, Asahi Glass, and Honda are mainly concerned with ultracapacitors, while Toyota and Sanyo have a greater focus on battery technology.

It is worth recalling, as discussed in Chapter 5, that Matsushita and its subsidiary Panasonic have entered a cross-licensing and technology development agreement with Energy Conversion Devices/Ovonic/Cobasys with regard to NiMH batteries. As was explained earlier, this agreement resulted from the settlement of a patent infringement suit brought by Energy Conversion Devices/Ovonic against Matsushita/Panasonic/Toyota. Given that DOE funded Energy Conversion Devices/Ovonic in its development of NiMH batteries, this suggests an indirect link between DOE funding and Matsushita's related patents.

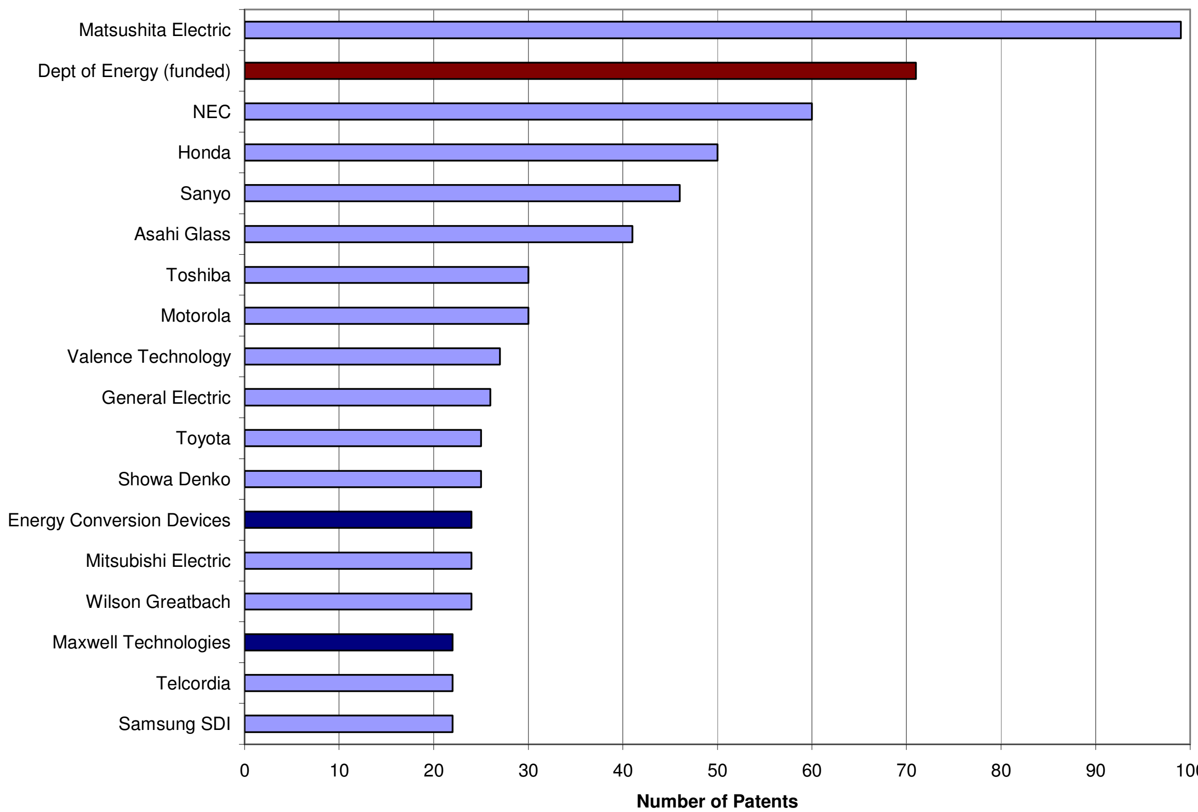


Figure 6-1. Organizations with largest number of HEV/PHEV/EV battery/ultracapacitor patents

In Figure 6-1, two organizations are highlighted in dark blue — Energy Conversion Devices and Maxwell Technologies. These are highlighted to call attention to the fact that there may be additional patents from these two organizations that appropriately should go in the DOE set.

As explained in Chapter 5, Energy Conversion Devices (i.e., the ECD Ovonics group) received multiple contracts from DOE through the industry consortium, USABC, and the public-partnership, PNGV, to develop NiMH batteries. The ECD Ovonics group has a number of patents covering this technology, as reflected in Figure 6-1. Yet, only three of its patents appeared in the OSTI database, and no other ECD Ovonics patents acknowledge DOE in their government interest field. As a result, while we believe that more of ECD Ovonics' patents may be linked to DOE funding, in the absence of an acknowledged formal link, they are listed separately from the DOE patents, to provide a conservative estimate for the DOE set.

In the case of Maxwell Technologies, the company received funding from DOE to develop ultracapacitors. Six of its ultracapacitor patents appear in the list of DOE patents. However, its 16 other ultracapacitor patents do not appear in the DOE list. Again, additional Maxwell patents may be linked, at least partially, to DOE funding, but, in the absence of formal links to DOE through the patents' government interest field, these other Maxwell's patents are listed separately — again to provide a conservative estimate for the DOE set.

Another organization worth noting, but that does not appear in Figure 6-1 because it is not among those with the largest number of HEV battery/ultracapacitor patents, is SAFT. As explained in Chapter 5, SAFT was also funded by DOE to develop NiMH batteries. However, only 10 of SAFT's patents are in the OSTI database. Again, additional SAFT patents may be linked to DOE funding, but there is no formal acknowledgement in the patents' government interest field, so these SAFT patents are also not included in the DOE set.

Hence, while acknowledged DOE-funded patents appear to be the second largest patent set in Figure 6-1, this may well be an understatement. If additional NiMH patents of ECD Ovonics, Maxwell, and SAFT appropriately fit in the DOE-funded set, this would likely make the DOE-funded patent set the largest.

6.1.2 Number of Patents Cited by HEV/PHEV/EV Battery/Ultracapacitor Patents

The organizations with the largest number of patents cited by HEV/PHEV/EV battery/ultracapacitor patents are shown in Figure 6-2. This figure is dominated by large organizations, due to the significant numbers of patents involved. The company at the bottom of this figure, General Motors, has over 50 different patents cited by the HEV/PHEV/EV battery/ultracapacitor patent set. Small specialist companies are unlikely to appear in the figure due to their smaller patent portfolios.

Of DOE-funded patents, 222 have been cited by HEV/PHEV/EV battery/ultracapacitor patents. Hence, while only 71 of DOE's patents are contained within the HEV/PHEV/EV battery/ultracapacitor filter, its influence on these technologies goes well beyond these patents. DOE-funded patents describing inventions covering component technologies such as electrolyte compositions, polymer electrodes and ceramic materials have all been cited by HEV/PHEV/EV battery/ultracapacitor patents. In addition, DOE-funded patents describing alternative forms of supplementary power for HEV/PHEV/EV, notably fuel cells, also have been cited extensively by the HEV/PHEV/EV battery/ultracapacitor patent set.

How does the 222 DOE-funded patents cited by HEV/PHEV/EV battery/ultracapacitor patents compare with those of other organizations? DOE has funded more patents cited by HEV/PHEV/EV battery/ultracapacitor patents than any other organization, except Matsushita Electric. More DOE-funded patents are cited than patents assigned to companies such as Sanyo, Honda, and General Motors. Indeed, if the ECD Ovonics and Maxwell patents were added to the DOE set, DOE would have funded more patents cited by HEV/PHEV/EV battery/ultracapacitor patents than all other organizations, including Matsushita.

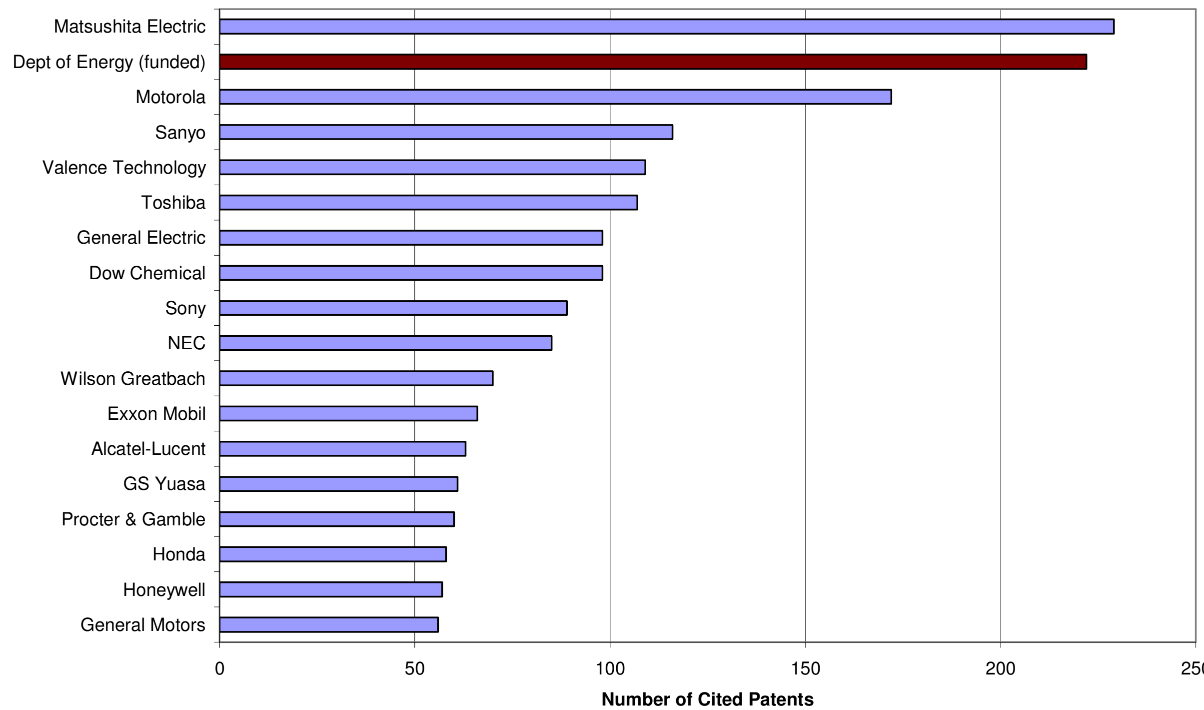


Figure 6-2. Organizations with largest number of patents cited by HEV/PHEV/EV battery/ultracapacitor patents

DOE has funded more patents cited by HEV/PHEV/EV battery/ultracapacitor patents than any other organization, except Matsushita Electric. More DOE-funded patents are cited than patents assigned to companies such as Sanyo, Honda, and General Motors. Indeed, if additional ECD Ovonics and Maxwell patents were appropriately added to the DOE set, as explained above, DOE would likely have funded more patents cited by HEV/PHEV/EV battery/ultracapacitor patents than all other organizations, including Matsushita.

6.1.3 Number and Frequency of Citations by HEV/PHEV/EV Battery/Ultracapacitor Patents

Beyond the question of how DOE compares with other organizations in terms of how many of its funded patents have been cited by HEV/PHEV/EV battery/ultracapacitor patents, is the question of how many times and at what rate have these patents been cited? Figure 6-3 helps to answer this question by showing the organizations whose patents have been cited most frequently by the HEV/PHEV/EV battery/ultracapacitor patents. In this figure, if a patent is cited by multiple HEV/PHEV/EV battery/ultracapacitor patents, this is reflected in the citation count. For example, if a patent in the DOE database is cited by 10 different HEV/PHEV/EV battery/ultracapacitor patents, this counts as 10 citations in Figure 6-3, whereas it counted as a single cited DOE patent in Figure 6-2.

The citations in Figure 6-3 are divided into self-citations and external citations. Self-citations are citations from an organization's own later patents, while external citations are citations from other organizations' patents. As Figure 6-3 shows, self-citations do not play a large role in the citation counts, with the exception of the high proportion of self-citation among the patents of Asahi Glass.

The portfolio of DOE-funded patents is the second most frequently cited, after the portfolio of Matsushita Electric. However, the frequency of citations for Matsushita Electric compared to DOE is much larger than the difference in their cited patent counts in Figure 6-2. HEV/PHEV/EV battery/ultracapacitor patents have given 482 citations to 222 different DOE-funded patents. Each DOE patent cited therefore has received an average of 2.17 citations. This is lower than the average number of citations for the patents of Matsushita (3.06) and Motorola (2.61), although it is higher than for Sanyo (1.84). (Citation frequency is computed by dividing the number of citations illustrated in Figure 6-3 by the number of cited patents illustrated in Figure 6-2.)

Figure 6-3 also includes organizations with the opposite citation profile; i.e., organizations with smaller numbers of highly cited patents. These companies include ECD Ovonics. The company's 50 cited patents have been cited by 164 later patents, an average of 3.16 citations per patent. These patents cover NiMH batteries, and materials for electrodes for use in such batteries.

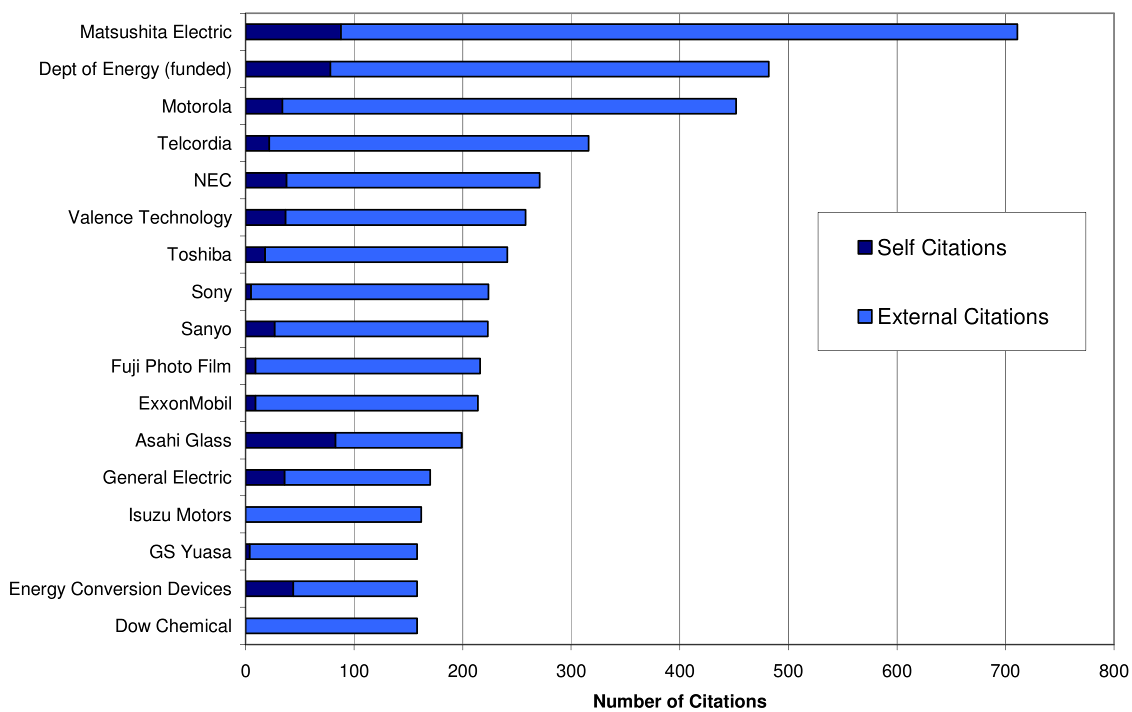


Figure 6-3. Organizations whose patents are cited most frequently by HEV/PHEV/EV battery/ultracapacitor patents

What is the significance of having a comparatively large number of cited patents, but a relatively low average citation rate, as is the case with DOE? The significance is that this is the type of pattern that would be expected if DOE funding has formed a broad foundation for HEV/PHEV/EV battery/ultracapacitor technology, rather than being at the center of specific developments in this technology. In contrast, the pattern for ECD Ovonics fits the case of a company at the center of specific developments in a technology — in this case NiMH batteries. The pattern observed for DOE is not necessarily a negative finding, since the role of government funding is often to develop foundation technologies upon which specific industries can be built.

6.1.4 Organizations Citing DOE-Funded Patents Most Frequently

Next we look at which organizations have cited the DOE set most frequently, and consider implications. Figure 6-4 lists the organizations whose HEV/PHEV/EV battery/ultracapacitor patents have cited DOE-funded patents most frequently and indicates the extent of each organization's citing. The pattern of citations shown in Figure 6-4 suggests that the inventions of the different groups funded by DOE are influencing each other. As a result, it appears that DOE funding not only has a direct impact on the group receiving the funding, but also an indirect impact on the other DOE-funded groups working in a similar area. This would appear to be a very positive characteristic of DOE's funding of different research groups.

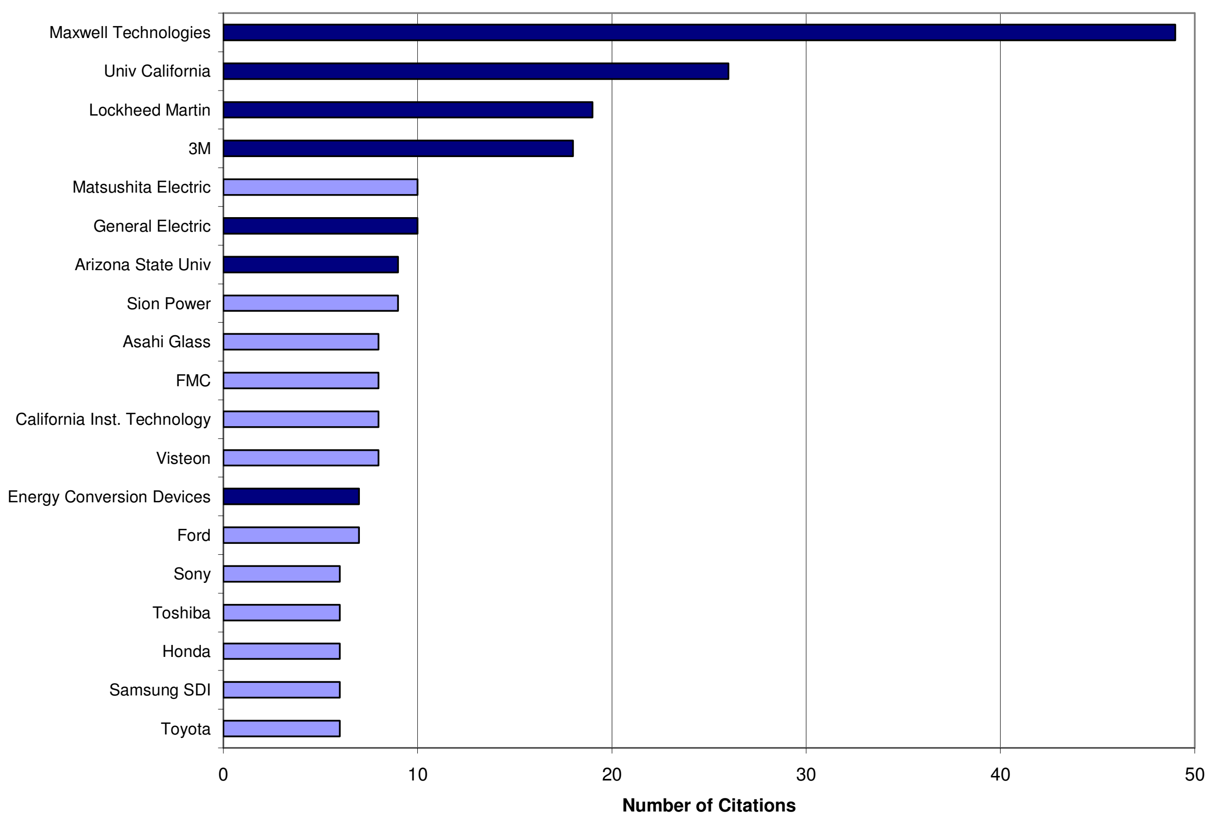


Figure 6-4. Organizations whose HEV/PHEV/EV battery/ultracapacitor patents cite DOE-funded patents most frequently
(Dark shading denotes an organization that has received DOE funding or operates a DOE lab)

The organizations at the top of this figure — Maxwell Technology, University of California, Lockheed Martin, and 3M — have all either received DOE funding, or operate DOE labs.

However, this does not mean that the citations provided by these organizations are simply self-citations of their own earlier inventions. For example, Maxwell's ultracapacitor patents cite a series of General Electric patents also describing ultracapacitors. Meanwhile, the University of California's battery patents cite various DOE patents describing composites and carbon foams. 3M's Li-ion patents cite patents from various DOE-funded organizations, but very few of these citations are to 3M's own patents.

DOE-funded patents are also cited by a variety of leading battery and ultracapacitor companies, notably Matsushita Electric and Sion Power; large car companies such as Ford, Honda, and Toyota; and universities including Arizona State and Caltech. Indeed, it is worth noting that there are 30 organizations other than DOE with more than 10 patents in the HEV/PHEV/EV battery/ultracapacitor patent set, and all 30 of these organizations have at least 1 HEV/PHEV/EV battery/ultracapacitor patent that cites a DOE patent. This citing pattern reflects the breadth of DOE's influence on the leading organizations in HEV/PHEV/EV battery/ultracapacitor technology.

The breadth of DOE's influence is also reflected in Figures 6-5 and 6-6. For each year starting in 1994, Figure 6-5 shows the percentage of all HEV/PHEV/EV battery/ultracapacitor patents that cite at least one DOE-funded patent. This percentage generally has been in the 15%-20 percent range for the past few years, with a spike of 32 percent in 2005. Overall, an average of 18 percent of all HEV/PHEV/EV battery/ultracapacitor patents issued since 1994 cite at least one DOE-funded patent (shown by the horizontal bar). This is an impressive figure, especially given that many of these cited patents are assigned to commercial enterprises with no direct links to DOE.

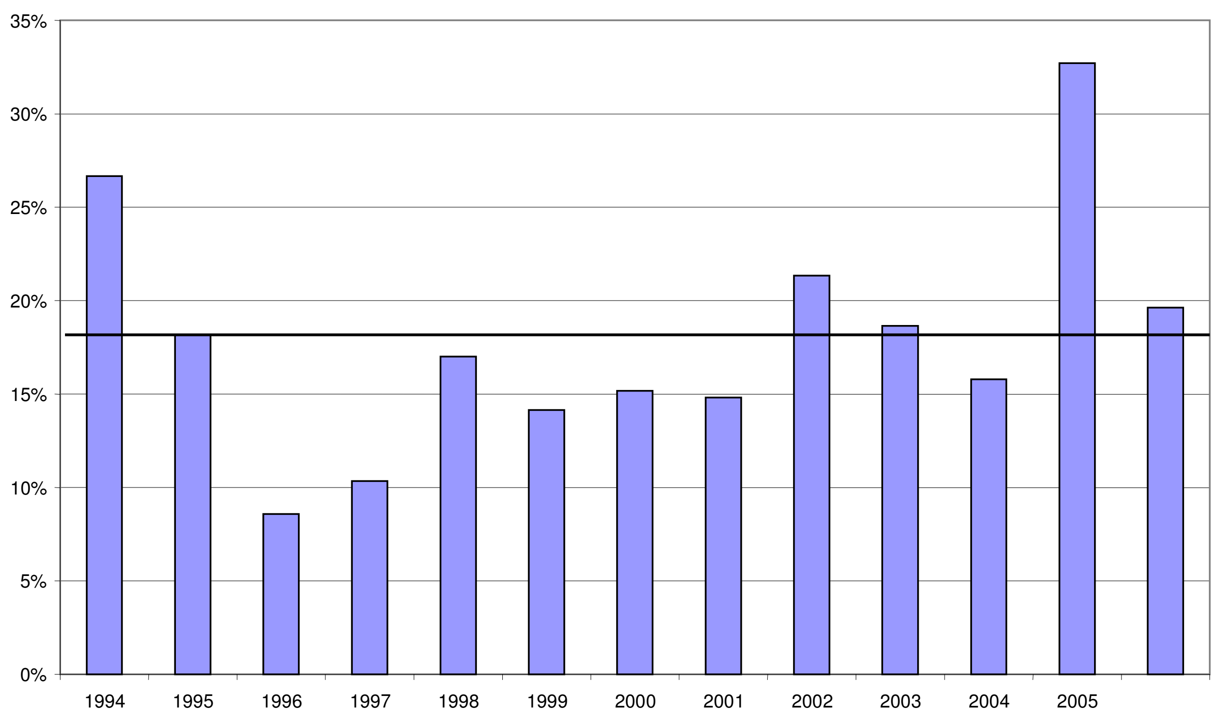


Figure 6-5. Percentage of HEV Battery/Ultracapacitor patents that cite at least one DOE patent

Figure 6-6 lists the leading HEV/PHEV/EV battery/ultracapacitor companies in declining order of the percentage of their patents citing at least one DOE patent. More than half of the HEV/PHEV/EV patents of Maxwell Technologies cite at least one DOE patent. Slightly more than 30 percent of General Electric HEV/PHEV/EV patents cite at least one DOE patent, and nearly 30 percent of those of ECD Ovonics. Major Japanese battery companies also have patents that cite DOE patents.

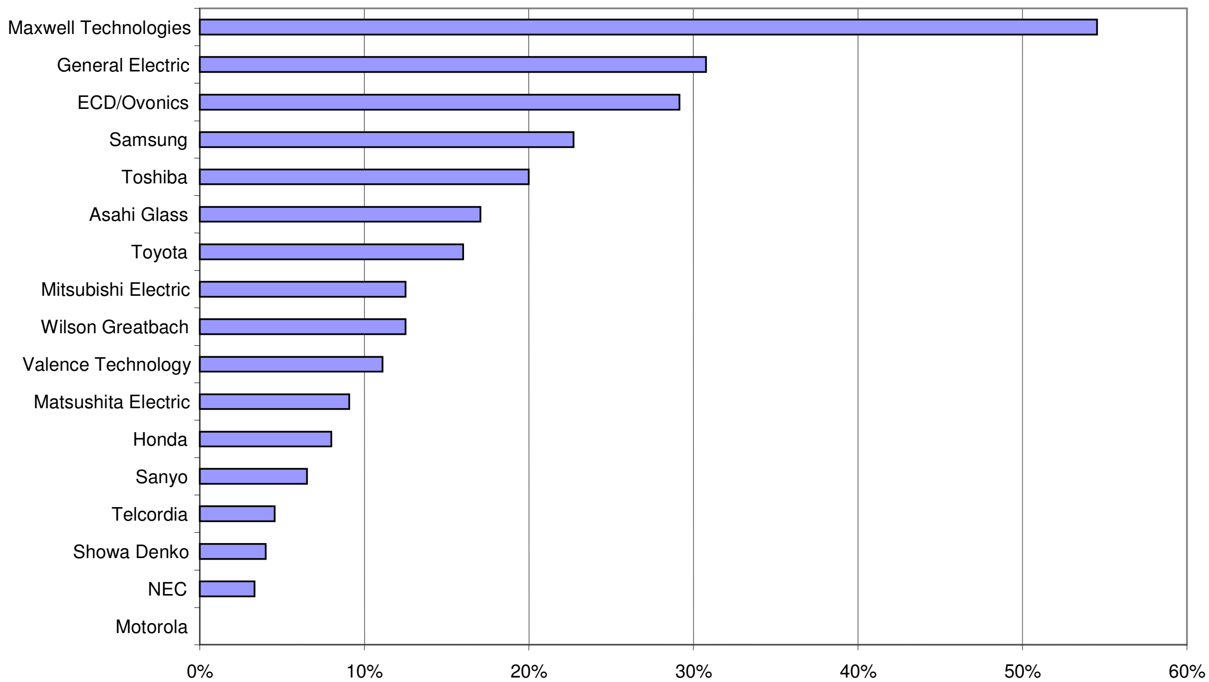


Figure 6-6. Leading HEV/PHEV/EV battery/ultracapacitor companies in declining order of the percentage of their patents citing at least one DOE patent

6.2 Patent Level Results

Having examined the impact of DOE-funded patents at the organizational level, we now examine the impact of this funding at the individual patent level. Patent-level results reveal specific DOE patents that have been particularly influential. They also reveal patents from other organizations that build extensively on DOE-funded patents.

6.2.1 Patents Citing the Largest Number of DOE-Funded Patents

Some HEV/PHEV/EV battery/ultracapacitor patents have built extensively on DOE-funded technologies. Table 6-1 lists those that cite the largest number of DOE-funded patents.

The list is headed by a 2005 patent assigned to Cymbet Corp. This patent, which describes the fabrication of thin-film energy storage devices, cites no fewer than 19 different DOE-funded patents. The other patents in Table 6-1 all cite at least five different DOE-funded patents.

Table 6. 1 HEV/PHEV/EV Battery/Ultracapacitor Patents Citing the Largest Number of DOE-Funded Patents

Citing Patent	Issue Year	# DOE Patents Cited	Assignee	Title
6962613	2005	19	Cymbet Corp	Low-temperature fabrication of thin-film energy-storage devices
6643119	2003	10	Maxwell Technologies	Electrochemical double-layer capacitor having carbon powder electrodes
6168884	2001	10	Lockheed Martin	Battery with an in-situ activation plated lithium anode
6955694	2005	10	Maxwell Technologies	Electrochemical double-layer capacitor having carbon powder electrodes
6402795	2002	8	Polyplus Battery	Plating metal negative electrodes under protective coatings
6723140	2004	8	Polyplus Battery	Plating metal negative electrodes under protective coatings
6706449	2004	8	Sion Power	Lithium anodes for electrochemical cells
6572993	2003	8	Visteon Corp	Fuel cell systems with controlled anode exhaust
7012124	2006	6	Arizona State Univ	Solid polymeric electrolytes for lithium batteries
5358802	1994	6	University of California	Doping of carbon foams for use in energy storage devices
6630262	2003	6	Greenstar Corp	Metal-gas cell battery with soft pocket
6428933	2002	6	3M	Lithium ion batteries with improved resistance to sustained self-heating
7170260	2007	5	Maxwell Technologies	Rapid charger for ultracapacitors
5336274	1994	5	University of California	Method for forming a cell separator for use in bipolar stack energy storage devices

They include a number of different Li-ion and ultracapacitor patents, reflecting the strength of DOE's influence on those technologies. They also include a patent assigned to Visteon describing a battery system for use in conjunction with fuel cells; an electrode plating patent assigned to Polyplus Battery; and a metal-gas patent assigned to Greenstar Corp.

6.2.2 Highly Cited HEV/PHEV/EV Battery/Ultracapacitor Patents That Cite DOE-Funded Patents

Table 6-2 contains a list of highly cited HEV/PHEV/EV patents that cite at least one DOE-funded patent. These are patents that have had a strong impact on later technological developments, having themselves built in some way on DOE-funded research. As such, DOE funding has formed part of the foundation for these important, highly cited patents.

The patents in Table 6-2 are sorted in descending order according to a normalized Citation Index, rather than by raw citation counts. One problem with raw citation counts is that older patents are likely to be more highly cited simply because they have had more time to accrue citations from later patents. A second problem is that average citation rates differ across technologies. In order to overcome these two problems, we normalize the citation counts by technology and year.

To normalize the citation counts, we first calculate the mean number of citations received by all patents from each year and technology (where technology is defined by U.S. Patent Office Classifications [POCs]). This mean value represents the expected citation count for a patent from a given year and technology. Dividing a patent's citation count by the corresponding expected count provides the Citation Index for that patent.

As an example, 11 subsequent patents have cited the patent at the head of Table 6-2, a lithium-ion patent assigned to Delphi, even though this patent was only issued in 2003. The mean number of citations received by 2003 patents in the same POC (429/316) is 1.499. Dividing the 11 citations received by the Delphi patent by this mean results in a Citation Index of 7.34 (11/1.499) for the Delphi patent. Hence, the Delphi patent has been cited by more than seven times as many subsequent patents as would be expected given its age and technology. It is worth noting that all of the patents in Table 6-2 have been cited by at least five subsequent patents, and all have Citation Indexes above two.

Two patents on this list may be of particular interest. The second patent on the list (Patent #6,402,795) is a 2002 patent assigned to Polyplus Battery, describing a method for forming lithium electrodes. This patent already has been cited by 13 patents, including citations from companies such as Sanyo, NEC, Sion Power (Moltech) and IBM. This Polyplus patent also appears in Table 6-1, as it cites eight different DOE patents. As such, this is an example of a patent building extensively on DOE-funded technology that is in turn influencing the next generation of battery technology as indicated by the comparatively heavy citing of it by other patents.

The second patent of particular interest is Patent #6,168,884, issued in 2001. This patent is assigned to Lockheed Martin, and describes a thin-film rechargeable battery designed as an improvement on Li-ion batteries. This Lockheed patent cites 10 different DOE patents. In

Table 6. 2 Highly Cited HEV/PHEV/EV Battery/Ultracapacitor Patents that Cite at Least One DOE Patent

Patent	Issue Year	Cites Received	Citation Index	Assignee	Title
6617078	2003	12	5.62	Delphi	Lithium ion rechargeable batteries utilizing chlorinated polymer blends
6402795	2002	25	8.08	Polyplus Battery	Plating metal negative electrodes under protective coatings
6168884	2001	29	5.31	Lockheed Martin	Battery with an in-situ activation plated lithium anode
6395405	2002	15	4.62	Unassigned	Hydrogen permeable membrane and hydride battery composition
5211933	1993	33	4.20	Telcordia	Method for preparation of LiCoO.sub.2 intercalation compound for use in secondary lithium batteries
5718877	1998	19	3.40	FMC	Highly homogeneous spinal Li.sub.1+x Mn.sub.2-x O.sub.4+y intercalation compounds and method for preparing same
6664006	2003	6	2.74	Lithium Power Technology	All-solid-state electrochemical device and method of manufacturing
5869208	1999	33	3.72	Fuji Photo Film	Lithium ion secondary battery
6094788	2000	40	4.65	Maxwell Technologies	Method of making a multi-electrode double-layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
5324599	1994	49	3.24	Matsushita Electric	Reversible electrode material
5260855	1993	56	3.23	Unassigned	Supercapacitors based on carbon foams
5631537	1997	41	3.14	Benchmarq Micro	Battery charge management/protection apparatus
6094338	2000	19	1.97	Mitsubishi Chemical	Electric double-layer capacitor
5961672	1999	22	3.66	Sion Power	Stabilized anode for lithium-polymer batteries
6265851	2001	18	2.85	PRI Automation	Ultracapacitor power supply for an electric vehicle
6413283	2002	16	3.25	General Electric	Sealed ultracapacitor
5512389	1996	31	2.43	Unassigned	Rechargeable non aqueous thin film lithium battery
5434020	1995	37	2.63	University of California	Continuous feed electrochemical cell with nonpacking particulate electrode

turn, it has been cited by 21 subsequent patents. These citations come from a range of organizations, both within and outside the HEV/PHEV/EV battery market. They include Matsushita Electric, NASA, and Front Edge Technology (a developer of nanoscale battery solutions). This Lockheed patent, which builds extensively on DOE-funded technology, may thus represent a new generation of lithium battery technology that, while not currently used in HEV/PHEV/EV batteries, could potentially be important to these future battery applications.

Another patent worth noting in Table 6-2 is Patent #6,265,851. This 2001 patent, assigned to PRI Automation, cites four different DOE patents, so does not quite reach the threshold for inclusion in Table 6-1. It describes an ultracapacitor for use in an electric vehicle, notably a monorail for materials handling. While this may not appear directly relevant to HEVs, this patent has been cited by 16 subsequent patents. Many of these citations come from patents describing HEV applications, notably patents assigned to Ford describing hybrid cars, and patents assigned to Kold Ban International describing ultracapacitors for use in trucks. As such, the PRI patent has influenced HEV technology, having itself built upon DOE-funded patents.

6.2.3 DOE-Funded Patents Cited Most Frequently by HEV/PHEV/EV Battery/Ultracapacitor Patents

Table 6-3 contains a list of the DOE-funded patents that have been cited by the largest number of HEV/PHEV/EV battery/ultracapacitor patents. The DOE patents in Table 6-3 describe a wide variety of technologies. A number of the patents describe ultracapacitors, and are assigned to Maxwell, General Electric, and the University of California. Maxwell's Patent #5,907,472 is the DOE-funded patent cited by the largest number of HEV/PHEV/EV battery/ultracapacitor patents. Figure 6-7 shows first-generation patent citations of this Maxwell patent. The accompanying table, Table 6-4, lists by company, patent number, date, and title the patents from Figure 6-7 that cite Maxwell's Patent #5,907,472. Out of the 19 citations to this patent, eight are from later Maxwell patents. However, the patent is also cited by battery and ultracapacitor patents from a number of other leading organizations, including NEC, Samsung, and Sony.

Table 6-3 also contains a number of DOE-funded patents describing Li-ion batteries. These patents are assigned to Lockheed Martin (operator of SNL) and Arizona State University. Lockheed Martin's Patent #5,314,765 is of particular interest. It has been cited by 70 later patents, as shown in Figure 6-8, which is more than four times as many citations as expected. The 10 patents listed in Table 6-5 are those citing #5,314,765 that are from the HEV/PHEV/EV battery/ultracapacitor set. These patents describe various aspects of Li-ion battery technology, and are assigned to a variety of companies, including Fuji Photo Film, Polyplus Battery, and Sion Power.

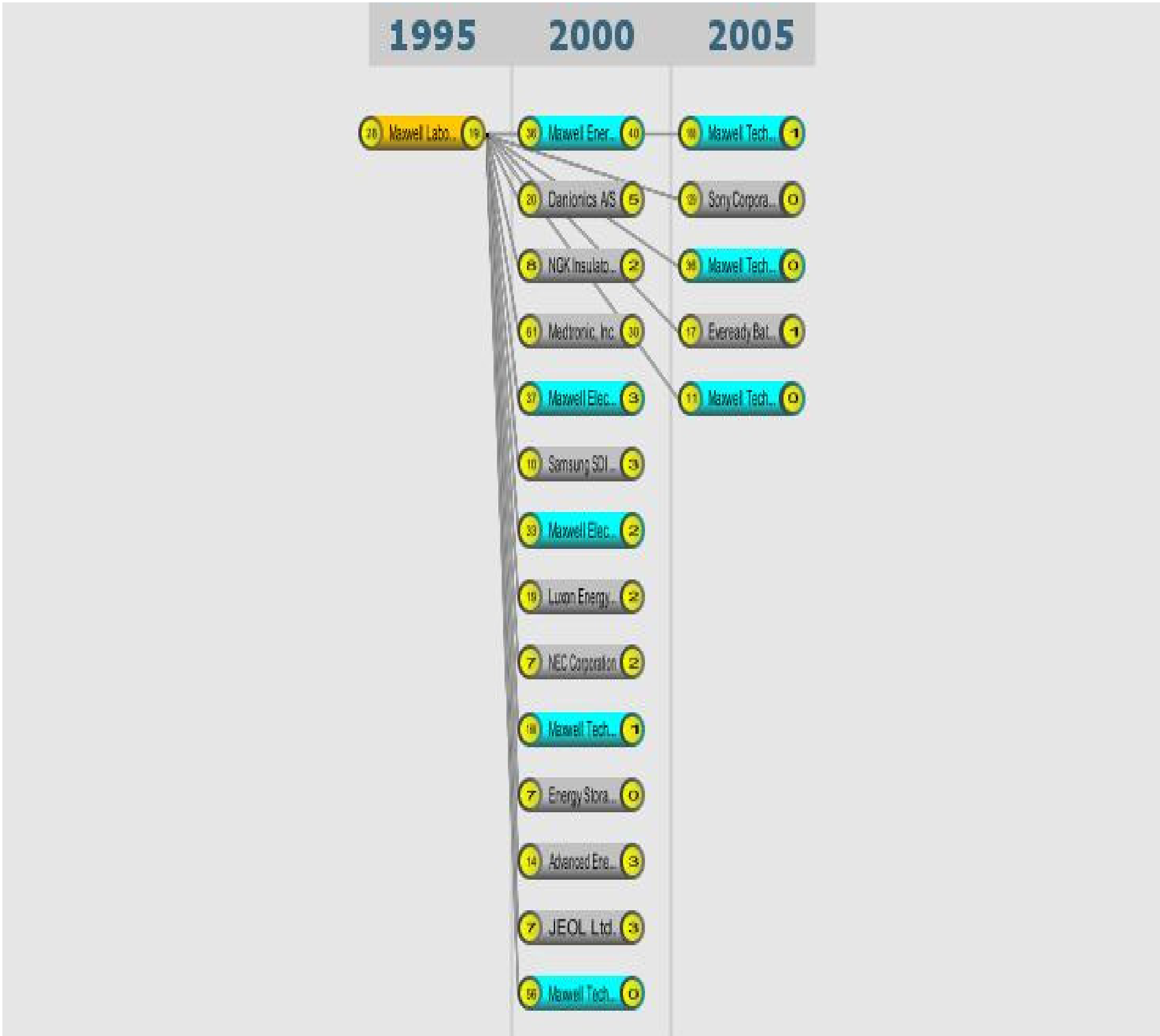
In addition to the Li-ion and ultracapacitor patents, Table 6-3 also contains DOE-funded patents describing other technologies. These include zinc air batteries, electrolytes and electrodes for batteries, and compositions for use in batteries and ultracapacitors. In the latter group, Patent #4,832,881 may be of particular interest. This 1989 patent describes carbon foams. Such foams have gone on to be used in ultracapacitors and as electrodes in Li-ion

Table 6. 3 DOE-Funded Patents Cited Most Frequently by HEV/PHEV/EV Battery/Ultracapacitor Patents

Patent	Issue Year	Cites from HEV/PHEV/EV Patents	Total Cites	Cite Index	Assignee	Title
5907472	1999	16	19	1.52	Maxwell Technologies	Multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
5260855	1993	13	56	3.23	Univ California	Supercapacitors based on carbon foams
5777428	1998	12	19	2.17	Maxwell Technologies	Aluminum-carbon composite electrode
5314765	1994	12	70	4.55	Lockheed Martin	Protective lithium ion conducting ceramic coating for lithium metal anodes and associate method
5862035	1999	7	18	1.44	Maxwell Technologies	Multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
5219679	1993	7	33	2.46	EIC Laboratories	Solid electrolytes
6094788	2000	7	40	4.65	Maxwell Technologies	Method of making a multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
6212061	2001	7	8	0.97	General Electric	Sealing an ultracapacitor
4448856	1984	7	17	1.59	DOE	Battery and fuel cell electrodes containing stainless steel charging additive
4842963	1989	6	52	3.62	DOE	Zinc electrode and rechargeable zinc air battery
4804592	1989	6	47	3.17	DOE	Composite electrode for use in electrochemical cells
5569520	1996	6	62	4.49	Lockheed Martin	Rechargeable lithium battery for use in applications requiring a low to high power output
5348822	1994	6	30	2.00	ECD/Ovonics	Chemically and compositionally modified solid solution disordered multiphase nickel hydroxide positive electrode for alkaline rechargeable electrochemical cells
5006424	1991	5	28	2.11	Univ California	Battery using a metal particle bed electrode
5219673	1993	5	34	2.52	Unassigned	Cell structure for electrochemical devices and method of making same

Table 6-3 DOE-Funded Patents Cited Most Frequently by HEV/PHEV/EV Battery/Ultracapacitor Patents, continued

5484670	1996	5	12	0.93	Arizona State Univ	Lithium ion conducting ionic electrolytes
4832881	1989	5	68	5.82	DOE	Low density microcellular carbon foams and method of preparation
5455126	1995	5	49	3.29	Lockheed Martin	Electro optical device including a nitrogen containing electrolyte
4238721	1980	5	89	9.73	DOE	System and method for charging electrochemical cells in series
5597660	1997	5	55	4.42	Lockheed Martin	Electrolyte for an electrochemical cell

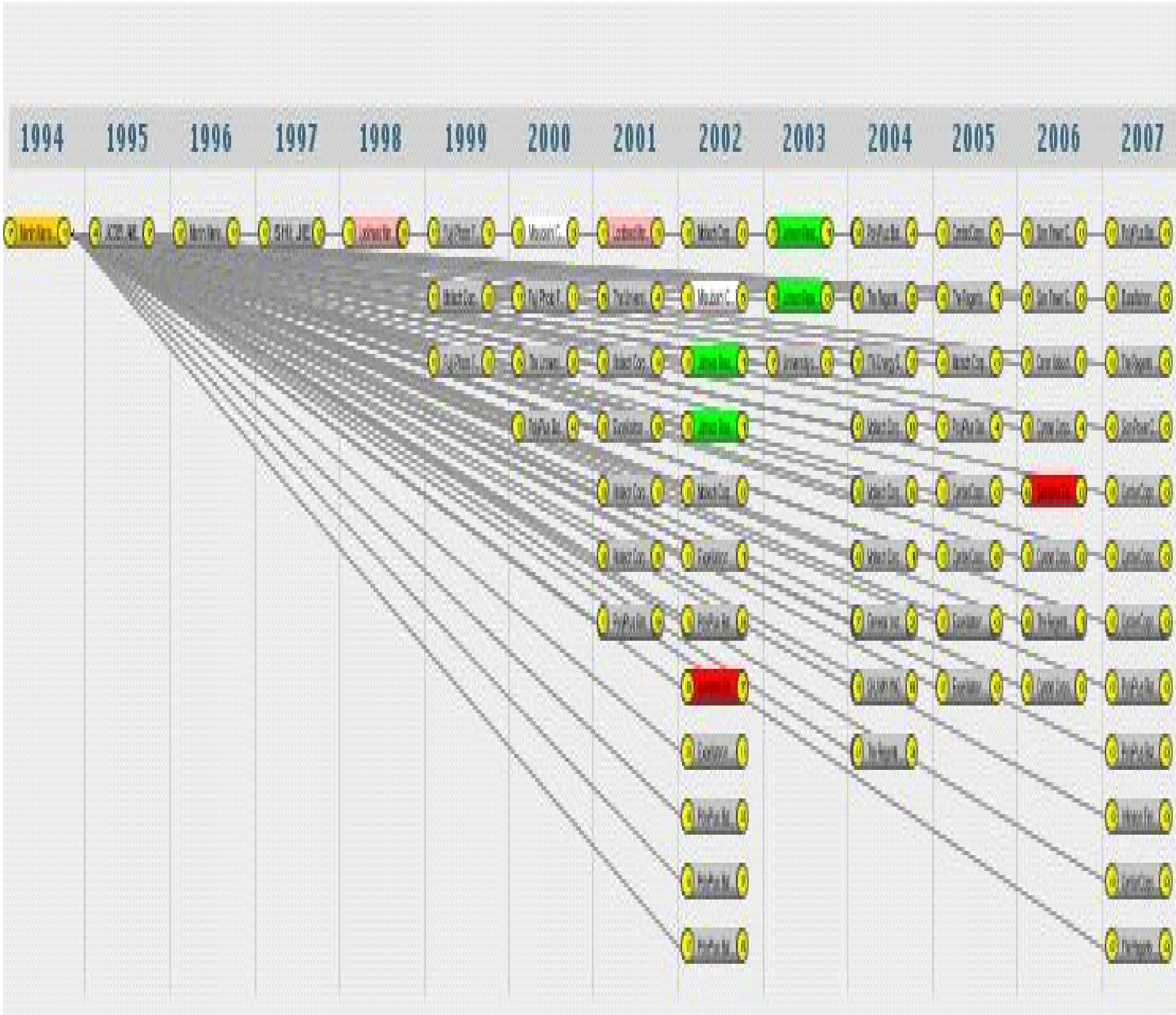


Note: Maxwell Self-Citations are highlighted in aqua. As previously noted, the Delphion-generated patent displays when copied and enlarged tend to lack visual sharpness. Table 6.4 clarifies the citation linkages.

Figure 6-7. Patents citing Maxwell Technologies' patent #5,907,472, issued in 1999, titled "multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes" (Shown in five-year increments)

Table 6. 4 Descriptions of Patents Citing Maxwell's Patent #5,907,472 from the HEV/PHEV/EV Set

Company	Patent Number	Year Issued	Title
Maxwell Technologies	6,094,788	2000	▪ Method of making a multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
	6,430,031	2002	▪ Low resistance bonding in a multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
	6,449,139	2002	▪ Multi-electrode double layer capacitor having hermetic electrolyte seal
	6,643,119	2003	▪ Electrochemical double layer capacitor having carbon powder electrodes
	6,813,139	2004	▪ Electrochemical double layer capacitor having carbon powder electrodes
	6,842,330	2005	▪ Multi-electrode double layer capacitor having hermetic electrolyte seal
	6,955,694	2005	▪ Electrochemical double layer capacitor having carbon powder electrodes
	7,170,260	2007	▪ Rapid charger for ultracapacitors
Sony	6,946,007	2005	▪ Electrochemical double layer capacitor having carbon powder electrodes
Jeol Ltd.	6,721,168	2004	▪ Electric double-layer capacitor and carbon material
Advanced Energy Technology	6,757,154	2004	▪ Double-layer capacitor components and method for preparing them
Luxon Energy Devices	6,510,043	2003	▪ Cylindrical high voltage supercapacitor having two separators
Energy Storage Systems	6,552,895	2003	▪ Flexible charge storage device
NEC Corp	6,507,479	2003	▪ Electric double-layer capacitor having a laminated overcoat
Danionic A/S	6,341,057	2002	▪ Double layer capacitor and its manufacturing method
Samsung SDI	6,387,566	2002	▪ Battery with laminated insulator/metal/insulator case



Note: Citations by Johnson Research & Development Company's patents are in green, by Mitsubishi Chemical in white, by Sumitomo Electric in red, and self-citations by Lockheed Martin in pink. As previously noted, the Delphion-generated patent displays when copied and enlarged tend to lack visual sharpness. See also Table 6.5.

Figure 6-8. Seventy patents citing Lockheed Martin's patent #5,314,765, issued 1994, titled "protective lithium ion conducting ceramic coating for lithium metal anodes and associate method" (shown in one-year increments)

Table 6. 5 Descriptions of Patents Citing Lockheed Martin's Patent #5,314,765 from the HEV/PHEV/EV Set

Company	Patent Number	Year Issued	Title
Lockheed Martin	6,168,884	2001	▪ Battery with an in-situ activation plated lithium anode
Fuji Photo Film	6,090,506	2000	▪ Nonaqueous secondary battery
Sion Power (Moltech)	6,706,449	2004	▪ Lithium anodes for electrochemical cells
Polyplus Battery	6,723,140	2004	▪ Plating metal negative electrodes under protective coatings
	6,402,794	2002	▪ Plating metal negative electrodes under protective coatings
Canon	7,081,320	2006	▪ High energy density secondary battery for repeated use
Cymbet	6,962,613	2005	▪ Low-temperature fabrication of thin-film energy-storage devices
Sumitomo Electric	6,365,300	2002	▪ Lithium secondary battery
Mitsubishi Chemical	6,040,078	2000	▪ Free form battery apparatus
Electrovaya	5,464,706	1995	▪ Current collector for lithium ion battery

batteries, even though the patent itself does not describe these later applications. As such, this is an example of DOE funding leading to a precursor technology for HEV/PHEV/EV batteries and ultracapacitors.

One may also note the presence of Patent #5,348,822 by ECD Ovonics in Table 6-3. This is the patent that was detailed in Figures 5-2 and 5-3 (Chapter 5), and supported by Tables 5-3 and Table C-1 (Appendix C). It is cited by patents describing NiMH batteries and HEV applications, and it is among the DOE-funded patents cited most frequently by HEV/PHEV/EV patents.

Figure 6-9 indicates further the importance of ECD Ovonics patents to later HEV/PHEV/EV patents, and shows that a wide range of organizations have cited its patents. The figure lists those organizations whose HEV/PHEV/EV battery/ultracapacitor patents cite the largest number of ECD Ovonics patents. The list includes many of the leading organizations in HEV/PHEV/EV battery technology, including Matsushita Electric as leading in its citing of ECD Ovonics patents, again suggesting a connection from the Japanese battery patents back to DOE-funded research. The list also includes Sanyo among those citing the largest number of ECD Ovonics patents. This heavy citing of ECD Ovonics patents reflects the broad impact of these patents in the development of NiMH battery technology. (Also, as was shown in Chapter 5, intense licensing of ECD Ovonics NiMH battery technology by many other battery companies, including major Japanese battery companies, also reflected the impact of these patents.)

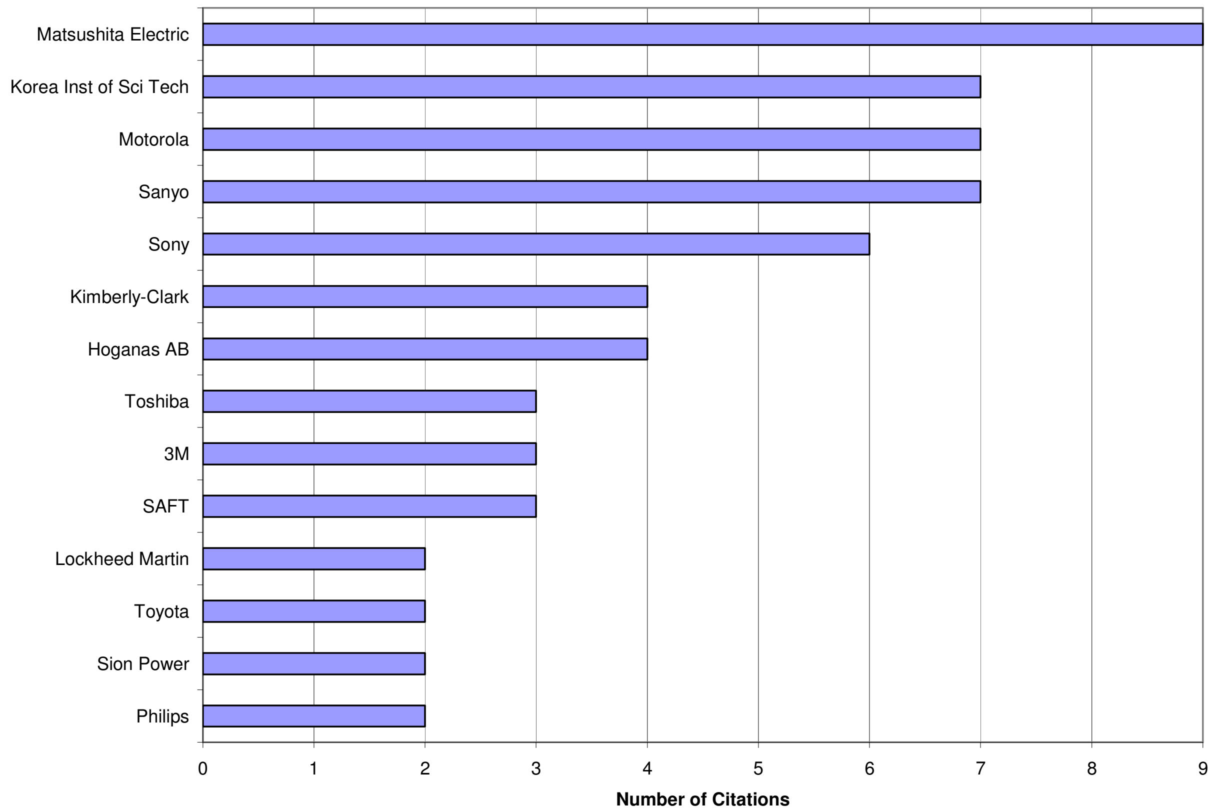


Figure 6-9. Organizations whose HEV/PHEV/EV battery/ultracapacitor patents cite the largest number of ECD Ovonics patents

Chapter 7. Summary of Conclusions

A principal conclusion of the study is that DOE/EERE has played a significant role in helping to establish the foundation for battery and ultracapacitor technologies for HEVs, PHEVs, and EVs. DOE/EERE funding is linked to three of the most prominent energy storage technologies for applications in these hybrid and electric vehicles: nickel metal hydride batteries, lithium-ion batteries, and ultracapacitors.

- Linkages were identified first through interviews with experts, substantiated by analysis of documents, licensing agreements, and limited patent tree analysis. Highlights of linkages identified by this approach include the following:

    - Funding by DOE — channeled through USABC — of multiple battery-company development projects, included funding for the development of the NiMH battery for HEVs by the ECD Ovonics group, and advances in Li-ion batteries by multiple DOE-funded companies.

    - General Motors and Daimler Chrysler produced their all-electric demonstration fleets in the early 1990s, powered with DOE-funded NiMH batteries.

    - NiMH batteries with higher power and extended cycle life were successfully demonstrated with DOE funding for use in HEVs, and subsequently auto makers used the batteries to demonstrate hybrid electric vehicles.

    - ECD Ovonics licensed its NiMH battery technology, developed in part with DOE funding, to major battery suppliers around the world.

    - Strong evidence was found of multiple indirect linkages from the major Japanese supplier of NiMH battery for HEVs (Matsushita Electric and its subsidiary Panasonic Battery) back to DOE-funding through licensing of ECD Ovonics NiMH technology, through citations of ECD Ovonics patents, and through the filing and resolution of a patent infringement case brought by ECD Ovonics against Matsushita Electric, Panasonic, and Toyota for infringing its NiMH battery technology.

    - Royalty payments to DOE have arisen from the licensing and incorporation of ECD Ovonics' technology in a NiMH battery provided by Sanyo for the Ford Hybrid Escape and the Honda Accord.

    - Battery test protocols developed by DOE national laboratories became the basis for automotive industry standards.

    - General Motors has included NiMH batteries from Cobasys, part of the ECD Ovonics group, in Saturn Aura Green Line Hybrid and Saturn VUE Green Line Hybrid.

- ANL recently has licensed its advanced rechargeable lithium battery technologies to NanoeXa to develop and transfer into commercial use for next-generation HEV and PHEV applications.

- General Motors has recently issued contracts to two partnerships of DOE-funded companies (a joint venture of Johnson Controls and SAFT and a partnership between A123Systems and Cobasys) for the supply of batteries for its prototype Saturn VUE Green Line Plug-in Hybrid.

▪ A second approach used to identify linkages was a broader patent citation analysis. This analysis aimed at determining connections between patents for HEV, PHEV, and EV battery and ultracapacitor technologies and patents resulting from DOE-funded research. Highlights from the broader patent citation analysis follow:

  - The patent citation analysis identified 71 DOE-funded patents that were contained within the larger set of HEV/PHEV/EV battery and ultracapacitor patents. This number was second after the 99 patents of Matsushita Electric, but greater than the 60 of NEC, the 50 of Honda, and the number of each of the other organizations among those with the largest number of HEV/PHEV/EV battery/ultracapacitor patents. Of the top seven organizations, all except DOE were Japanese companies.

  - The patent citation analysis identified 222 DOE-funded patents that were cited by the larger set of HEV/PHEV/EV battery and ultracapacitor patents. This group of cited DOE-funded patents included component technologies that were not identified directly by applying a patent filter. The number for DOE was just slightly less than that for Matsushita Electric.

  - The 222 DOE-funded patents were cited 482 times for an average of 2.17 citations per patent. Among companies with the largest number of cited patents, DOE's average number of citations was lower than that of Matsushita (3.06) and Motorola (2.61), but higher than the average of Sanyo (1.84).

  - The large number of cited DOE patents, along with their relatively low average citation rate, suggests that DOE funding has formed a broad foundation for HEV/PHEV/EV battery/ultracapacitor technology, rather than being at the center of specific developments in this technology. This is not necessarily a negative finding, since the role of government funding is often to develop foundation technologies upon which industries can be built.

  - Overall, almost one in five HEV/PHEV/EV battery/ultracapacitor patents issued since 1994 has cited at least one DOE-funded patent. Citing patents include those of many leading organizations in HEV/PHEV/EV battery/ultracapacitor technology. In comparison, only one organization has more of its patents in this area cited by other HEV/PHEV/EV battery/ultracapacitor patents than DOE: Matsushita Electric with 26 percent.

For further comparison, 15 percent cite Motorola; 11 percent cite Sanyo; 10 percent cite NEC; 5 percent cite Honda; and 3 percent cite Toyota.

- There are 30 organizations other than DOE with more than 10 patents in the filtered HEV/PHEV/EV battery/ultracapacitor patent set. All thirty of these organizations have at least 1 HEV/PHEV/EV battery/ultracapacitor patents that cites a DOE-funded patent.

- The patents of different organizations funded by DOE cite each other extensively. This pattern of citations suggests that the inventions of the different groups funded by DOE are influencing each other. As a result, it appears that DOE funding not only has a direct impact on the group receiving funding, but also an indirect impact on the other DOE-funded groups working in similar areas. This would appear to be a very positive characteristic of DOE's funding of different research groups.

- There are a number of highly cited HEV/PHEV/EV battery/ultracapacitor patents that themselves cite preceding DOE-funded patents. These include patents for a variety of technologies, notably lithium-ion batteries and ultracapacitors. This reflects DOE's role in forming part of the foundation for patents that underlie battery and ultracapacitor technologies.

- The results discussed above do not include in the DOE patent set a series of highly cited NiMH patents assigned to ECD Ovonics. That DOE-funded this firm to develop nickel metal hydride technology — as indicated by expert interview, document review, and royalty payments from the firm to the U.S. government — appears established. However, only 3 of the 50 ECD Ovonics patents cited by the HEV/PHEV/EV patent set appear in DOE's OSTI database, and none of them acknowledges a DOE government interest. Hence, while we believe that some of the additional ECD Ovonics patents may in part reflect DOE funding, in the absence of formal proof, they are separately treated. A result may be an understatement of patent linkages through ECD Ovonics.

Multiple approaches have been taken in the study — interviews with experts, review of documents and licensing, and patent citation analysis — to examine linkages between battery and ultracapacitor technologies for HEVs/PHEVs/EVs and DOE-funded energy storage research for vehicles. The application of these approaches have demonstrated a number of linkages, including substantial linkages from three of the most prominent energy storage technologies for applications in hybrid and electric vehicles — NiMH batteries, Li-ion batteries, and ultracapacitors — to DOE-funded research in vehicle energy storage.

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Interviewees

Mr. Tien Duong, Team Leader, Vehicle Technologies, VT Program, EERE, Interview conducted at DOE Forrestal Building, Washington, DC, October 19, 2006.

Mr. Ken Heitner, Team Leader, Vehicle Technologies, VT Program, EERE (retired), Telephone interview, supplemented by e-mail exchanges, conducted October 19–24, 2006.

Mr. Gary Henriksen, Manager, Battery Technology Department, Chemical Engineering Division, ANL's Transportation Technology R&D Center, Telephone interview conducted March 5, 2007.

Mr. David Howell, Staff Member, Vehicle Technologies, VT Program, EERE, Interview conducted at DOE Forrestal Building, Washington, DC, October 19, 2006.

Professor John Newman, Researcher in the Materials Sciences Division, Department of Chemical Engineering, University of California, LBNL, Telephone interview conducted March 9, 2007.

Dr. Philip Patterson Jr., Industry Economist, Office of Planning, Budget, and Analysis, EERE, Interview conducted at DOE Forrestal Building, Washington, DC, October 19, 2006.

Appendix A. Methodological Details in Support of Chapter 2

A.1 Interview Guide used for Interviews with Experts*

INTERVIEW GUIDE
EERE-Vehicle Technologies and National Laboratories Research Managers

Name: ____
Title/Position: ____
Program: ____
Contact Information: ____
____

Knowledge Base/Specialty:
____
____

Date of Interview: _____________
Type of Interview: __ In Person __ Telephone __ Email

Length of Interview: _____________

Background: Explanation of study purpose and technology focus.

Five Planned Topics of Discussion:

I. History (Timeline) of Energy Storage R&D for Applications in HEVs, PHEVs, and EVs

Identify major milestones in the history since the mid-to-late 1970s and associated organizational roles.

Identify major shifts in the DOE program or changes in emphasis.

II. DOE's Most Noteworthy Contributions to Energy Storage R&D and the Related Role of DOE in Industry's Advancement toward Successful Commercialization of HEVs, PHEVs, EVs

What have been major contributions of FreedomCAR and Fuel Partnership (VT Program) in advancing energy storage technologies?

Technical:
Other:

What have been major contributions of Partnership for a New Generation of Vehicles (PNGV) in advancing energy storage technologies?

Technical:
Other:

What have been major contributions of earlier DOE programs in advancing energy storage technologies?

Technical:
Other:

With respect to energy storage, what role has DOE played in industry advancements toward successful commercialization of HEVs, PHEVs, and EVs?

With respect to energy storage, how do you think the world would be different without DOE's R&D programs in energy storage technologies?

III. State of Energy Storage Technologies for HEV, PHEV, and EV

Contrast (in layman's terms) the state-of-the-art of energy storage technologies for HEVs, PHEVs, and EVs now versus where they stood in the mid-to-late 1970s. (Breakout by sub-types of technology if needed)

State-of-art in mid-to-late 1970s:

State-of-art in 2006:

IV. Specific Linkages between DOE-supported R&D in Energy Storage Technologies and the Technologies in Existing (or soon to be) HEVs, PHEVs, and EVs

Are you aware of specific results of DOE energy storage R&D that can be found in HEVs, PHEVs, and EVs on the market today (or expected soon)? If so, what?

If you were trying to document linkages between DOE energy storage R&D and specific energy storage technologies found in existing vehicles, who would you talk to?

Are you aware of DOE-funded patents or publications that likely have been cited by these manufacturers? If so, can you identify them?

V. Other Comments or Advice

What have I missed?

What question would you most like to have answered by this study?

Do you have any suggestions for key words for use in patent citation searches?

Do you have suggestions for other DOE people now or previously involved in battery R&D whom I should interview?

End of Interview Guide

*Note: This interview guide was used for the initial interviews with DOE staff and is geared largely towards forward-tracing rather than the backward-tracing approach taken by the aggregate patent citation analysis. As noted in Chapter 2, the study contains both forward- and backward-tracing elements.

A.2 Methodological Details for Identifying HEV Battery and Ultracapacitor Patents

As discussed in the methodology presentation of Chapter 2, in order to identify patents related to HEV batteries and ultracapacitors, we designed a patent filter based on Patent Office Classifications (POCs) and keywords. Designing a patent filter such as this is an iterative process, in which various combinations of keywords and POCs are considered in order to generate a suitable patent set. As a quality control check, we manually reviewed the results of the filtering process. This included manually checking all titles included in the final set, along with a sample of full abstracts. Any irrelevant patents were removed as a result of this process.

Patent Office Classifications – The first stage in designing a patent filter is determining relevant POCs. Many keywords and acronyms have multiple meanings according to the technology they describe, so it is important to focus on the correct application of these keywords. We identified a number of POCs that are particularly relevant to HEV batteries and ultracapacitors, as shown in Table A-1.

Table A-1 – Patent Office Classifications relevant to HEV Batteries/Ultracapacitors

Patent Office Classification	Description
Batteries	
29/623.1-5	Electric battery cell making
180/65.02	Electric vehicle combined with non-electric drive means
320	Electricity: Battery or capacitor charging or discharging

429	Chemistry: Electrical current producing apparatus, product, and process
903	Hybrid electric vehicles

Ultracapacitors

29/25.03	Electrolytic device making (e.g., capacitor)
320	Electricity: Battery or capacitor charging or discharging
361	Electricity: Electrical systems and devices
particularly 361/502	Double-layer electrolytic capacitor
and 361/503	Liquid electrolytic capacitor
429	Chemistry: Electrical current producing apparatus, product, and process
903	Hybrid electric vehicles

Some of these POCs are general in nature, such as 320 and 429, which describe batteries and similar devices. Others are much more specific, and describe particular processes, such as the production of batteries, or electrolytes for ultracapacitors. There is also a specific POC dedicated to double-layer electrolytic capacitors (ultracapacitors).

POC 903, entitled Hybrid Electric Vehicles, is slightly different from the other POCs in the table, in that it has only been added recently by the U.S. Patent Office. Recent patents may thus be issued with a 903 classification. Furthermore, the patent office has also added 903 classifications to older patents that were issued before this POC existed. For example, a battery patent may have been issued with POCs in the 320 or 429 classes. If this patent is regarded as relevant to hybrid vehicles, a 903 classification may have been added, so the patent now has its original classes, and a new 903 classification.

It is worth noting that there are two POCs that were expected to be particularly relevant to this patent filter, but this turned out not to be the case. These POCs are both part of POC 903 (POC 903/907: Electricity storage (e.g., battery, capacitor) and POC 903/943: Control of electrical storage means (e.g., battery)). From their title, it would seem that patents in these POCs would be directly related to batteries for hybrid electric vehicles. However, while some of these patents were indeed concerned with battery technology, a much larger number described the operation and control of hybrid electric vehicles. The battery is part of these control systems, which explains the use of the battery-related POC. Despite this, the main focus of many of these patents was on the broader HEV system, rather than the battery itself. Patents in these POCs were not therefore included automatically, but only if they described battery technology.

Keywords – Having generated a list of relevant POCs, we then selected keywords to identify HEV batteries and ultracapacitors. In the process of identifying relevant battery patents, we found that, once the search was restricted to the relevant POCs, the term “battery” has little discriminatory power. For example, many of the patents in POCs 320 and 429 are concerned with batteries, so adding a battery keyword does not narrow this set to patents relevant to HEV applications.

We therefore used keywords related to specific types of batteries that are used, or have been proposed for use, in HEVs. These keywords are listed in Table A-2.

Table A-2 Keywords Used in Patent Filter for HEV Batteries/Ultracapacitors

Batteries	
Lithium ion	Ni Zn
Li ion	Zinc bromine
Li-ion	ZnBr
Lithium and polymer	Zn Br
Nickel metal	Zinc air
NiMH	Sodium nickel chloride
Ni MH	NaNiCl
Nickel and hydride	Na NiCL
Nickel zinc	Valve regulated lead acid
NiZn	VRLA
Ultracapacitors	
Ultracapacitor	High-power capacitor
Ultra capacitor	(Electric) Double-layer capacitor
Supercapacitor	(Electric) Dual-layer capacitor
Super capacitor	EDLC
Pseudocapacitor	Carbon polymer and capacitor
Pseudo capacitor	Conducting polymer and capacitor

Our previous research showed that NiMH batteries are currently the most prevalent in HEVs, while Li-ion batteries are being targeted for use in next-generation HEVs and PHEVs. We therefore searched for patents using these terms, including their abbreviations and chemical formulas.

It should be noted that patent applicants often do not refer to the specific application for their invention, since this may narrow the scope of the patent's coverage. For example, a patent that claims the use of a Li-ion battery in a hybrid vehicle will be narrower than the same patent that describes only the battery, and does not refer to the vehicle application.

The keywords used in our filter thus may introduce patents describing Li-ion and NiMH batteries that are not necessarily designed for use in HEVs. For example, Li-ion batteries are used in a wide range of electronic equipment, so our filter picks up patents from a variety of electronics companies. Such patents may make no mention of their proposed application, but rather describe a particular advance in battery technology.

The only straightforward way to exclude such patents would be based on assignee, with all patents assigned to electronics companies being excluded. However, this may not be appropriate, since there may be advances made by electronics companies in battery technology that could also be applied in HEVs. As a result, we kept all Li-ion and NiMH patents in our analysis.

Having said this, we did not extend our analysis to lithium or nickel batteries in general. The reason for this is that there are very large numbers of patents that describe lithium batteries, and also nickel cadmium batteries. However, to our knowledge neither of these battery types has been used, or proposed for use, in HEVs. As such, including patents simply because they use the terms “lithium” or “nickel” is likely to introduce large numbers of irrelevant patents to our analysis; therefore, such a search strategy was avoided.

There are also a number of other battery types that have been proposed for use in HEVs, including lithium polymer; nickel zinc; zinc bromine; zinc air; sodium nickel chloride; and valve-regulated lead acid. We therefore searched for these battery types using the keywords, chemical names, and abbreviations listed in Table A-2.

The search for ultracapacitor patents was more straightforward in terms of keywords, since the term “ultracapacitor” has a much more specific meaning than the term “battery.” We therefore searched for ultracapacitor patents using a variety of terms for capacitors, such as ultracapacitor, supercapacitor, pseudocapacitor, and double-layer capacitor. We also searched for alternative spellings of these terms, notably the addition of a space before the word “capacitor.” These terms are listed in Table A-2.

Patent Filter Summary – our initial search focused on patents in the POCs in Table A-1 that have at least one of the keywords in Table A-2 in either their title or abstract. We supplemented this search with additional searches with slightly relaxed POC and keyword constraints, in order to identify relevant patents that use non-standard terminology, or have been placed in unusual POCs by the patent examiner. For example, we searched for patents using the keywords in Table A-2 that were not in the POCs in Table A-1. We also examined patents in the specific POCs in Table A-1 (such as 361/502 and 29/623.1-5) that do not use any of the keywords in Table A-2. We then added to our patent set those patents that appeared to be relevant from these searches.

As a result of the filtering process, we identified 1,670 U.S. patents issued since 1976 that are related to batteries and ultracapacitors with potential applications in HEVs, PHEVs, or EVs.

Appendix B. Institutional Analysis Extended from Chapter 4

B.1 More on DOE National Laboratories Involved in Energy Storage Research and Testing

Argonne National Laboratory (ANL)
ANL is managed by the University of Chicago, Argonne, for the DOE's Office of Science. With funding from DOE, ANL conducts battery research and operates a battery testing facility. In fact, ANL established the nation's first battery test facility, the National Battery Test Laboratory, in 1976, in response to the first oil shocks. The early testing was focused on the EV batteries of that time. With the formation of PNGV and its partnership with USABC — and the shift in focus over time from EVs to HEVs — the focus of ANL's battery testing shifted to HEV batteries. Its current focus is on battery testing for both HEV and PHEV batteries. ANL's testing laboratory, now called the Electrochemical Analysis and Diagnostics Laboratory, is operated by ANL's Chemical Engineering Division. It is a computer-operated test facility that allows performance and lifetime tests of both individual cells and multicell battery modules under simulated real-world conditions to provide independent evaluations of advanced battery systems for vehicle applications.[174]

ANL collaborates with DOE's other main battery test facility, operated by Idaho National Laboratory (INL), on the testing of battery deliverables resulting from USABC contracts. The USABC decides where a given battery resulting from a contract it has funded will be tested — either at ANL or INL. In addition to the contract testing, ANL performs benchmark testing of batteries developed by battery developers located world-wide. Additionally, in order to conduct the tests, ANL and INL develop testing protocols. As explained in Chapter 5, these testing activities provide important linkages to downstream innovations.[175]

DOE's VT Program has designated ANL as the lead national laboratory for the simulation, validation, and laboratory evaluation of PHEV and the technologies required for PHEV.[176] This role is demonstrated in a recent brochure from Argonne's Transportation Technology R&D Center entitled, "Argonne, the Source for PHEV Data," which highlights ANL's award-winning vehicle simulation software, its mobile advanced technology test bed, its capabilities for state-of-the-art testing, and its collaboration with INL for technology viability assessment, including on-board data acquisition systems for collecting in-fleet performance data for HEVs and PHEVs.[177]

From a research standpoint, ANL's focus has centered from the beginning on lithium-based batteries. In fact, the laboratory invented Li-ion sulfate battery technology, and performed

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[174] Interview with Mr. Gary Henriksen, Manager, Battery Technology Department, Chemical Engineering Division, ANL's Transportation Technology R&D Center, March 5, 2007.
[175] Ibid.
[176] ANL Media Center, "EPRI, Argonne to assess commercial viability of plug-in hybrid electric vehicles," www.anl.gov/Media_Center/News/2006/news061127.html.
[177] ANL Brochure, "Argonne, the Source for PHEV Data," www.cmt.anl.gov/Source_for_PHEV_Data.pdf.

early work under a CRADA on lithium-polymer batteries for use in EVs. In 1998, ANL's Chemical Engineering Division was instrumental in establishing the Advanced Technology Development (ATD) Program, an R&D program for research on advanced Li-ion batteries involving multiple national laboratories.[178]

Currently, ANL's battery research program is focused on extending the capabilities of Li-ion batteries in four areas: (1) extending battery life from its current limit of about 8 years up to 15 years, (2) reducing cost to $20/kW, (3) improving battery abuse tolerance, and (4) improving performance under low-temperature conditions.[179]

Lawrence Berkeley National Laboratory (LBNL)

LBL, managed by the University of California, conducts research across a wide range of scientific disciplines in 17 scientific divisions, and also hosts 4 national user facilities. The lines between the University of California and the government laboratory are blurred. LBNL is located on the campus of the university; professors in the university often also work in LBNL and on VT Program's long-term research programs.[180]

Energy storage R&D is located within LBNL's Environmental Energy Technologies Division. Within the Division, the Advanced Energy Technologies Research Department is focused on Li-ion batteries, including battery development and analysis, mathematical modeling, diagnosis, and novel materials synthesis for cathodes, anodes, and electrolytes. Battery research began in LBNL in 1978, with formation of the Exploratory Technology Research (ETR) Program.[181]

The Berkeley Electrochemical Research Council (BERC) manages DOE's Batteries for Advanced Transportation Technologies (BATT) Program.[182] BATT is the long-term electrochemical research arm of the DOE's VT Program. BATT's focus is on new materials for next-generation batteries for HEVs and EVs, covering six task areas: cell development, anodes, electrolytes, cathodes, diagnostics, and modeling.

Of the funding for BERC from EERE's VT Program, about 60–70 percent has gone to fund research within LBNL, and about 30–40 percent has gone to fund energy storage proposals from universities, coordinated by BERC. Reportedly, there are currently about 22 principal investigators working in the BATT Program, including faculty from MIT, State University of New York, Clemson, and University of Texas.[183]

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[178] Argonne National Laboratory Fact Sheet, "Lithium-ion Battery Research and Development," available at: www.cmt.anl.gov/Science_and_Technology/Batteries/Publications/Lithium-Ion_Battery_Research.pdf.

[179] Interview with Mr. Gary Henriksen, Manager, Battery Technology Department, Chemical Engineering Division, ANL's Transportation Technology R&D Center, March 5, 2007.

[180] Interview with Professor John Newman, Researcher in the Materials Sciences Division, Department of Chemical Engineering, University of California, LBL, March 9, 2007.

[181] LBL's Energy Storage Technologies Research is described at www.lbl.gov.

[182] Professor John Newman, who was interviewed for this study, provides oversight of BERC.

[183] Ibid.

Idaho National Laboratory (INL)
INL is operated by the Battelle Energy Alliance Team, comprising Battelle, BWX Technologies, Washington Group International, EPRI, and MIT. INL is the lead laboratory for advanced high-power energy storage testing and evaluation for DOE and the USABC.

Energy storage research at INL resides in its Energy Efficiency and Natural Resources (EE&NR) Directorate, within its Transportation Technologies and Infrastructure Department. Its Energy Storage Technologies Laboratory is a leader in the testing and characterization of advanced battery and ultracapacitor technologies, and is DOE's lead facility for hybrid vehicle battery performance and life-characterization studies.[184]

INL collaborates with NREL in an Advanced Vehicle Testing Activity (AVTA), which provides benchmark data on the performance of vehicles that feature one or more advanced technologies, among them advanced batteries. Information from the AVTA supports decisions of fleet managers and the public about acquiring advanced technology vehicles. During the 1990s, for example, the AVTA tested many full size electric cars, including those made by GM, Ford, Chevrolet, Toyota, and others. In 2003, the AVTA tested three light-duty HEVs then available: the Honda Civic, Honda Insight, and Toyota Prius. As of late August 2006, performance data for HEV vehicles included tests for the 2004 Chevrolet Silverado, the 2005 Ford Escape, the 2006 Lexus RX400H SUV, and the 2006 Toyota Highlander. By early 2007, testing reports for the 2007 Toyota Camry had been added to HEV performance data.[185]

During the latter half of 2006, AVTA initiated PHEV testing. This activity has included development of PHEV testing specifications and procedures, procurement of several converted PHEV models, and beginning data collection. Eventually the testing results will be posted on the AVTA web pages.[186]

Among INL's advanced energy storage publications are multiple test manuals, including those listed below:[187]

Battery Technology Life Verification Test Manual
FreedomCAR 42V Battery Test Manual
FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles
PNGV Battery Test Manual Revision 3
Electric Vehicle Capacitor Test Procedures Manual Oct, 1994
USABC Electric Vehicle Battery Test Procedures Manual, Revision 2

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[184] INL's Energy Storage Technologies Laboratory described at www.inl.gov/transportation.
[185] "Hybrid Electric Vehicles," http://avt.inl.gov/hev.shtml.
[186] "Plug-in Hybrid Electric Vehicles," http://avt.inl.gov/phev.shtml.
[187] "Advanced Energy Storage Publications: Manuals," http://avt.inl.gov/energy_storage_lib.shtml. Note that in addition to INL researchers, authors of these manuals included researchers from ANL, LBNL, SNL, and the USABC.

Brookhaven National Laboratory (BNL)
BNL is operated by Brookhaven Science Associates, a not-for-profit research management company, under contract with DOE's Office of Science.

Researchers in the Alternative Energy Program of BNL's National Synchrotron Light Source (NSLS) are researching promising new cathode materials, testing new electrolyte compounds that are environmentally friendly and less expensive than those previously available, for use in Li-ion batteries for HEVs. The focus has been on how the cathode material behaves in the charging process, a factor important to HEV performance. The new material compounds were developed under a CRADA between Brookhaven and Gould Electronics, Inc. A patent for a new kind of electrolyte for Li-ion batteries was issued to Brookhaven researchers in the Energy Sciences and Technology Department in 2000.[188]

Sandia National Laboratories (SNL)
SNL, operated by Sandia Corporation, a Lockheed Martin company, was started in 1949, to develop science-based technologies in support of national security. SNL's energy storage research for hybrid vehicles is performed by its Power Sources Technology Group.

In 1981, DOE designated the Power Sources Technology Group as a lead center for exploratory development and testing of rechargeable battery systems, including applications for EVs.[189] The mission of this Group was to develop, design, produce, support, and evaluate battery and other energy storage technologies for government agencies and industry. Today's FreedomCAR work of the Group centers mainly on battery abuse tolerance and also on developing a method to predict Li-ion battery life using both empirical modeling and mechanistic modeling.

The Group has onsite facilities for fabricating developmental and prototype lithium batteries, which can serve as a backup production supplier of thermal batteries if the need arises.[190] The Group's staff members also serve on the USABC Technical Team. The Group's focus is on extending the life, increasing the safety, and reducing the cost of Li-ion batteries for hybrid vehicles.

SNL developed abuse test procedures for electric vehicle batteries that the Society of Automotive Engineers adopted in 1999. In 2005, SNL published a manual providing a common framework for abuse testing of batteries, capacitors, and combinations of the two, for use in HEVs and EVs.[191] Reportedly, the SAE soon will soon adopt SNL's improved abuse test procedures for Li-ion batteries as national standards.[192]

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[188] The patent was for a new kind of electrolyte for Li-ion batteries, issued to Hung Sulk Lee, Xiao-Sing Yang, James McBreen, and Caili Xiang. Brookhaven Bulletin, "Patent Gives Battery Research a Charge," Vol. 54, No. 24, July 21, 2000.
[189] The Power Sources Technology Group long had responsibility for batteries for weapons systems, dating back to the 1950s. Information provided at the Power Sources Technology Group's Web site: www.sandia.gov/pstg/history.html.
[190] Power Sources Technology Group, op cit., www.sandia.gov/pstg/Capabilities.html.
[191] Daniel H. Doughty and Chris C. Crafts, "FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications," Sandia Report, SAND2005-3123, August 2006. (Note

National Renewable Energy Laboratory (NREL)
NREL, which began operating in 1977 as the Solar Energy Research Institute, became a DOE national laboratory in 1991 and was renamed. Managed for DOE by Midwest Research Institute and Battelle, NREL is the principal research laboratory of DOE's EERE. NREL's R&D focuses on developing innovations to advance energy usage for powering buildings and vehicles, and it emphasizes technology transfer into energy markets. R&D emphasis is on enhancing the thermal performance and life-cycle costs of battery modules and ultracapacitors. Modeling and simulation are used to assess trade-offs among various energy storage parameters for use in different types of vehicles.

NREL's Center for Transportation Technologies and Systems (CTTS) leads R&D in innovative vehicle and fuel technologies and supports the FreedomCAR and Fuel Partnership. Within CTTS's Advanced Vehicle Systems Group is the Energy Storage Project, funded by DOE's VT Program, and having lead responsibility at NREL for conducting research on energy storage technologies for HEVs, PHEVs, EVs, and Fuel Cell Vehicles (FCVs).[193] NREL energy storage researchers work closely with USABC, and through it, with a number of industry participants, including DaimlerChrysler, Ford, and General Motors, as well as energy storage developers and suppliers, to achieve FreedomCAR energy storage goals. The research team has won several prestigious awards.[194]

In 2004, a collaborative research effort on advanced battery systems for HEV, EV, and fuel cell vehicle (FCV) applications was launched between energy storage researchers in NREL and counterparts in the Korea Automotive Research Institute (KATECH). Their collaboration focused on the performance of Li-ion polymer cells.

While NREL's research during the 1990s centered on technologies for HEVs, now it is focused on PHEV technologies. For example, a recent joint study between NREL and a major U.S. electricity and natural gas company, Xcel Energy, investigated ways the use of PHEVs might reduce the overall expense of owning a vehicle and reduce harmful vehicles emissions by as much as 50%. NERL used its cutting-edge computer-modeling program to estimate measures of the impact of mass penetration of PHEVs and the amount of energy from the electric power grid needed to keep them charged.[195]

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that this manual represents an update to earlier work by SNL presented on the Society of Automotive Engineers Recommended Practice SAE J2464.)

[192] "Sandia researchers seek ways to make lithium-ion batteries work longer, safer; Batteries could soon replace standard nickel-metal hydride batteries in hybrid vehicles," SNL News Release, January 16, 2006. www.sandia.gov/new-center/news-releases/2006/renew-energy-batt/battery2.html.

[193] NREL's energy storage research is described at its Web site, www.nrel.gov/vehiclesandfuels/energystorage/.

[194] In 2001, NREL's energy storage team, together with 2 companies and the USABC, received an R&D 100 Award for an innovation that extended the life of lead acid batteries by 300 percent to 400%. In 2004, NREL's energy storage team leader and coauthors from the University of Toledo and Daimler Chrysler received the Vincent Bendix Automotive Electronics Engineering Award for the best paper at the Society of Automotive Engineers 2004 World Congress for work sponsored by the FreedomCAR and Fuel Partnership.

[195] "Xcel/NREL study: With a smart grid, plug-in hybrid electric vehicles could have system benefits," NREL News Release, February 21, 2007.

B.2 A List of Test Manuals Published by ANL, INL, and SNL for Use of USABC

Table B.2-1 lists manuals of test procedures published by ANL, INL, and SNL, sometimes in collaboration with USABC, but in all cases for use by USABC. These manuals are posted by USCAR at its Web site.

Table B.2-1 Test Procedures for Hybrid Electric Energy Storage Systems

Name of Manual	Description	Source/Reference	Date
Battery Technology Life Verification Test Manual	Advanced Technology Development Program for Lithium-Ion Batteries	Idaho National Engineering & Environmental Laboratory INEEL/EXT-04-01986	February 2005
Electric Vehicle Battery Test Procedures Manual	Summarizes procedures for performing battery testing being sponsored by the USABC	Team of USABC and DOE national lab staff and based on experience and methods developed at 3 national labs — ANL, INEL, and SNL	January 1996
Energy Storage Abuse Test Manual for EV and HEV Applications	Incorporates improvements and refinements to SAE J2464	Sandia National Laboratories SAND 2005-3123	June 2005
FreedomCAR 42V Battery Test Manual	Defines a series of tests for 42V energy storage systems	Idaho National Engineering & Environmental Laboratory DOE/ID-11070	April 2003
FreedomCAR Power Assist Battery Test Manual	Characterize performance of energy storage devices relative to FreedomCAR requirements	Idaho National Engineering & Environmental Laboratory DOE/ID-11069	October 2003

FreedomCAR Ultracapacitor Test Manual	FreedomCAR Ultracapacitor Performance Requirements	USABC Battery Information	undated
USABC Abuse Test Procedures Manual	Tests for electrochemical storage systems adopted by the SAE in SAE J2464	USABC/SNL CRADA No. SC961447	July 1999

B.3 Highlights from the National Research Council's Reviews of PNGV and FreedomCAR

According to NRC's 1997 review of PNGV's 1996 research program, the potential candidate energy storage technologies at that time included the NiMH battery, the Li-ion battery, the ultracapacitor, and the flywheel. Of the most important technical accomplishments in 1996, the NRC review listed demonstration of a subscale, high-power, Li-ion battery cell for 100,000 shallow cycles, and development and construction of demonstration vehicles, including GM's EV-1. The review concluded that successful development of both the flywheel and ultracapacitor were "well beyond the time frame of the program."[196]

An NRC review of PNGV published in 1998 and covering 1997 concluded that, "although significant progress continues to be made in technology development, the economic viability of the HEV remains to be demonstrated." It also concluded that PNGV-fostered competition had hastened European and Japanese efforts along similar lines, with the Europeans establishing the European Car of Tomorrow Task Force in 1995 and the Japanese launching the Japan Clean Air Program in 1996. The NRC review concluded that the U.S. PNGV contractors were "well ahead" in energy storage technology for HEV applications.[197] (Yet, only two years later Toyota and Honda were able to move ahead of U.S. vehicle manufacturers in bringing to market HEVs.)

An NRC review of PNGV published in 1999 and covering 1998 concluded that, "The electrochemical battery is still the most promising technology for energy storage in hybrid electric vehicles (HEVs)."[198] It noted that the energy and power goals at that time appeared attainable, but safety, cycle-life, and calendar-life targets were questionable. The review concluded:

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[196] National Academies, National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Third Report (1997), p. 4.

[197] There is other evidence that the U.S. PNGV contractors were "well ahead." Yet, in 1999, Japanese companies began to introduce HEVs in the United States, ahead of U.S. companies. According to one source, the Japanese companies were willing sell below their costs while U.S. companies were not.

[198] National Academies, National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report (1999), p. 3.

Hybrids are being developed, and have been demonstrated outside the program with batteries that fall far short of the very aggressive PNGV performance and cost targets. ...if energy-storage performance goals are relaxed and redefined, the hybrid concept could be implemented and tested even though the batteries currently under development are unlikely to meet the present targets. (NRC Fifth Review of PNGV, p. 40.)

The next NRC review of PNGV's research program, published in 2000 and covering 1999, continued to assess goals and progress. It noted that NiMH batteries were a less risky backup system for nearer-term deployment in concept vehicles, though Li-ion batteries offered greater potential for higher energy and energy efficiency. According to the review, "Meeting the cost and life goals remains a major challenge."[199]

The final NRC review of PNGV's research program was published in 2001 and focused on 2000. Among other things, the review recognized the growing success of the Japanese with HEVs despite the facts that their HEV batteries had not demonstrated PNGV target life, and their battery costs exceeded PNGV cost targets by more than three times.[200] The committee recommended a reconsideration of PNGV's goals.

In the fall of 2004, the NRC formed a new committee to review the FreedomCAR and Fuel Partnership Program, and, in 2005, the first review was published. The review recognized that ultracapacitors, which appeared to have been dropped previously, were a part of the FreedomCAR.[201] It also gave attention to energy storage capacity needed to enable PHEVs.[202]

The 2005 NRC review identified the total DOE budget for all energy storage technologies in FY04 and FY05 as $22.3 and $23.0 million, respectively, of which over 75 percent funded battery development efforts, with smaller amounts going to applied battery research and long-term exploratory research.[203] The review encouraged DOE to increase its R&D aimed at high-energy batteries as needed to support EVs and PHEVs.[204]

The 2005 NRC review also commended the VT Program for expanding its battery development efforts to include both basic and applied research, and encouraged the search for new materials and solutions to problems of abuse tolerance, cost, and calendar life.[205] Among the committee's conclusions were that FreedomCAR's plan is well thought out and well executed; participation by both energy companies and automobile manufacturers is essential;

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[199] National Academies, National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Sixth Report (2000), p. 40.
[200] National Academies, National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report (2001), p. 45.
[201] The National Academies, NRC, Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report (2005), p. 52.
[202] Ibid, p. 52.
[203] Ibid, p. 72.
[204] Ibid, pp. 76-77.
[205] Ibid, p. 73.

government and industry experts working together to help advance the needed technologies is important; and consistent codes and standards play a critical role.[206]

In addition to the series of dedicated NRC reviews of PNGV and FreedomCAR, NRC also assessed advanced high-energy batteries for electric vehicles as part of a broader overview of the benefits and costs of DOE's applied energy programs from 1978 to 2000, in *Was It Worth It?*[207] The NRC assessment begins by noting "The nemesis for the electric car has always been the battery, its energy storage and power capacity, its life cycle, its weight, and its cost." It examines DOE's effort in the context of its participation in USABC, and efforts to develop advanced high-energy batteries for electric cars.

Was It Worth It? summarized DOE funding for advanced high-energy battery R&D for EVs for the period FY 1978 through FY 2001, as shown in Table B.3-1. Column 1 of the table shows funding for high-energy battery development programs, supporting work, and benchmarking. Column 2 shows DOE funding for directed exploratory research programs; i.e., research in developing new electrode and electrolyte materials for advanced batteries and advanced diagnostics and modeling techniques for understanding battery operations at the national laboratories and at supporting universities. Column 3 shows DOE's funding for USABC cooperative R&D with the USABC research phase identified in parentheses. According to the NRC report, the amounts in column 3 represent a 50 percent industry cost share through USABC in Phase I, a 55 percent cost share in Phase II, and a 65 percent in Phase III.

In its findings, the NRC committee concluded that the initial targets of DOE and USABC for NiMH batteries for the mid-term and lithium-based batteries for the long-term had not been fully met at the time of the study, but "considerable progress toward them has been made."[208] It concluded that batteries remain too costly and too heavy, their cycle life too short, that they provide EVs with a travel range that is too short before recharging is necessary, and that recycling is still of concern due to toxic materials. At the same time, the committee also concluded that the transition from NiMH batteries to lithium-based batteries for the EV "may occur in the near future."

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[206] Ibid, pp. 97-98.
[207] NRC, *Was It Worth It,* 2001.
[208] Ibid, p. 141.

Table B.3-1. DOE Funding for Advanced High-Energy Battery R&D for EVs (millions of 1999 dollars)

Fiscal Year	DOE Development Programs, Supporting Work, and Benchmarking	Directed Exploratory Research Programs	DOE Portion of USABC Cooperative R&D (Phase)
1978[a]	12.4	0.9	
1979[a]	11.2	1.7	
1980	13.7	6.1	
1981	11.8	6.6	
1982	8.7	9.7	
1983	8.6	6.9	
1984	6.6	6.6	
1985	2.9	6.6	
1986	3.0	5.4	
1987	4.1	4.4	
1988	6.7	4.0	
1989	8.3	3.6	
1990	8.8	4.0	
1991	5.1	5.7	7.9 (I)
1992	0.6	3.0	24.1 (I)
1993	2.8[b]	4.4	24.7 (I)
1994	0.3	3.6	29.6 (I)
1995	0.2	2.2	23.8 (I)
1996	0.4	2.0	15.8 (II)
1997	0.0	2.4	13.3 (II)
1998	0.5	3.3	12.1 (II)
1999	0.8	2.9	3.7 (II)
2000	1.0	3.7	3.0 (III)
2001	1.0	2.7	4.0 (III)

[a]Data for FY 1978 and FY 1979 are estimated from combined program elements in program budget.
[b]Included work on an air battery system that was not part of USABC.
Original source: Office of Energy Efficiency. 2000. OEE Letter response to questions from the Committee on Benefits of DOE R&D in Energy Efficiency and Fossil Energy: Advanced Batteries for Electric Vehicles Program. December 4.

Source: the body of the table is reproduced from NRC's *Energy Research at DOE: Was It Worth It?* (2001), Table E-29, p. 141.

Note: the table is re-titled from the original to make it clearer that the NRC study was focused on the high-energy battery R&D for EVs and not the high-power battery R&D for hybrids. The original table made it confusing as to what funding is captured by the NRC table because the original is titled simply, "DOE Funding for Advanced Battery R&D." Yet the accompanying text refers to amounts of about $15 million per year for high-power energy storage for hybrid vehicles under PNGV continuing in 1996 and 1997, amounts clearly not included in the table.

In its benefit/cost matrix, the report stated DOE R&D costs as $376 million; private industry cost share as $169 million; and realized benefits as "few thus far" because "electric vehicles have achieved little market penetration." In the category of options benefits, the report noted the provision of potentially expanded markets for NiMH and/or lithium-based systems if the cost of alternatives increases, as well as potentially large environmental and security benefits. It also noted knowledge benefits/costs in terms of avoidance of duplication of R&D costs through collaboration, and potential economic, environmental, and security benefits from future use of increased scientific understanding of batteries for diverse applications.[209]

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[209] Ibid, p. 142.

Appendix C. Material in Support of Chapter 5

C.1 More from Interviews and Document Review

C.1.1 Opinions of DOE/EERE Research Managers on Linkages through the ECD Ovonics Group

The interviews conducted with DOE research managers all highlighted the central role played by the ECD Ovonics Group in developing the batteries used in the EV1 electric car of the 1990s and now used in HEVs — development that was, according to the research managers — funded in part by DOE through the USABC.[210] For example, according to Mr. Tien Duong, Team Leader of Energy Storage Research in DOE's VT Program:

> *A company called Energy Conversion Devices was responsible for developing NiMH batteries with DOE funding. The battery is being used in HEVs. In fact, almost all HEVs are using NiMH batteries for which the "background technology" was licensed from Energy Conversion Devices. The company received a contract from USABC to develop the technology that was jointly funded by DOE and the car companies. USABC provided about 19%; DOE provided 50%; and the rest was cost-shared by Energy Conversion Devices.* (Mr. Tien Duong, Interview, Washington, D.C., October 20, 2006.)

Mr. Tien went on to explain that DOE also played a critical role in the formation of the USABC, through which the contract work with ECD Ovonics was arranged.

According to Mr. Ken Heitner, retired DOE research manager with a long history working with its research program on energy storage technologies:

> *The most prominent contribution in electric vehicles was the development of the NiMH EV batteries by Ovonic and SAFT* [another company that received DOE funding through the USABC, addressed below]. *These were used in demonstration fleets of DaimlerChrysler's and General Motors' electric vehicles. ...The basic work for the NiMH batteries used in all hybrid vehicles was done in the United States. Japanese companies licensed the technology and proceeded to develop a wide variety of battery products.* (Mr. Ken Heitner, Interview and Background Notes, October 24, 2006.)

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[210] Interviews with Mr. Tien Duong, Mr. Ken Heitner (retired), Mr. David Howell, and Dr. Philip Patterson, Jr., all now or formerly with EERE, without exception emphasized the importance of the work performed by the referenced companies, with funding by DOE, in producing energy storage solutions that enabled the current generation of HEVs. (Detailed affiliations of interviewees are provided at the end of the list of References.)

According to Mr. David Howell, current researcher in the DOE VT Program:

> *Cobasys of Energy Conversion Devices is a prime place to look for linkages. A lot of our early work was with ECD. When they went to production, it was through Cobasys. There was an agreement made between Cobasys/Energy Conversion Devices and Panasonic on licensing of the NiMH technology. Panasonic batteries are in Toyota's hybrids. The IP is based on DOE funding. Sanyo, which has batteries in American hybrids, also licensed the technology from Cobasys/Energy Conversion Devices. There may be some differences in the design and cost breaks, but the NiMH battery technology is pretty much the same.* (Mr. David Howell, Interview, Washington, D.C., October 19, 2006.)

Dr. Philip Patterson, an EERE industry economist, also attributed the development of NiMH batteries to USABC/DOE-supported R&D carried out by the ECD Ovonics Group. He noted as an indication of this linkage that royalties are paid to DOE by ECD Ovonics Group from its NiMH-derived revenue stream. (See Subsection 5.1.4 for more on royalty payments.)

C.1.2 Interview and Document Review Information on Linkages through Test Manuals

Opinions of DOE/EERE Program Staff:

According to EERE's Tien Duong, the battery test manuals provide a good example of one way national laboratory research is disseminated.

> *This standard is talked about; it has been highly influential. The consortia with industry were essential in making it happen. Even though DOE labs did the testing requirement for hybrids in 1996, it is still valid, and it is a Society of Automotive Engineers standard.* (Mr. Tien Duong, Interview, Washington, DC, October 20, 2006.)

According to the research manager, it is important that all the companies — whether Japanese, Korean, European, or U.S. — all use the same standard protocol to evaluate their batteries. "Because all batteries are tested based on the same standard, it is possible to know exactly where every one is; how the batteries of suppliers in other countries stand relative to yours. I can't say enough to emphasize the significance of having a standard protocol."[211]

Opinions of National Laboratory Managers:

When asked if he knew of any paths of influence from ANL to commercially available or expected-soon-to-be-available HEVs and PHEVs, the manager of ANL's Battery Technology Department emphasized ANL's battery testing program — in addition to ANL's battery research program. The ANL manager noted specific benefits from the testing program: benefits to the battery developers who have access to independent, consistent testing; and

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[211] Interview with Mr. Tien Duong, October 20, 2006.

benefits to USABC industry and government members who are able to determine performance results and to assess state-of-the-art capabilities through benchmarking results and to assess the comparative position of U.S. producers.[212]

Opinions of a Battery Developer:

A recent example of a battery developer who chose to publicize the test results of its Li-ion battery technology developed under a USABC/DOE contract is provided by Ener1, Inc., a subsidiary of EnerDel. The CEO of EnerDel noted that the "test results from an independent laboratory confirm that our lithium-ion battery technology has great promise for the hybrid electric vehicle market." The Vice Chairman of Ener1, Inc., called the test results "another step toward validation of our lithium-ion battery technology for the hybrid electric vehicle market" and "further evidence that we are accelerating our work toward commercialization..."[213]

Opinions of Third-Party Evaluators:

According the NRC's seventh review of the PNGV program in 2001, "Cell and module testing has increased in importance and effort, and it is benefiting from the program's independent battery testing capability at the Idaho National Environmental and Engineering Laboratory." The review also noted that for the first time (in 2000), HEV battery testing by the PNGV included Japanese prototypical Li-ion batteries.[214]

C.1.3 ANL's Publications and Patents Identified as Particularly Important to Downstream Innovations

ANL's battery research manager identified the following list of seven publications from ANL's Battery Technology Department as examples of those particularly important to downstream progress.[215]

- M. M. Thackeray, *Manganese Oxides for Lithium Batteries*, Progress in Solid State Chemistry, 25, 1 (1997). (**297 citations)**
- M. M. Thackeray, C. S. Johnson, J. T. Vaughey, N. Li and S. A. Hackney, *Advances in Manganese-Oxide 'Composite' Electrodes for Lithium-Ion Batteries*, J. Mater. Chem. 15, 2257 (2005). (**5 citations)**
- K. D. Kepler, J. T. Vaughey and M. M. Thackeray, *$Li_xCu_6Sn_5$ (0<x<13): An Intermetallic Insertion Electrode for Rechargeable Lithium Batteries*, Electrochemical and Solid State Letters, 2, 307 (1999). (**153 citations)**

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[212] Interview with Mr. Gary Henriksen, Manager, ANL's Battery Technology Department, March 5, 2007.
[213] "Ener1's EnerDel Subsidiary Announces Lithium Ion Battery Test Results for Advanced High-Power Batteries for Hybrid Vehicle Applications," News Release, February 21, 2007 (www.marketwire.com/mw/release_html_b1?release_id=217885&tsource=3).
[214] National Academies, National Research Council, Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report (2001), p. 45.
[215] Post-interview material provided by Mr. Gary Henriksen, March 5&6, 2007.

- Kang, S.H., and Amine, K.
  Layered $Li(Li_{0.2}Ni_{0.15+0.5z}Co_{0.10}Mn_{0.55-0.5z})O_{2z}F_{z(z)}$ cathode materials for Li-ion secondary batteries, *Journal of Power Sources*, 146 (1-2): 654–657 Sp. Issue, August 26, 2005
- Zonghai Chen, J. Liu, and K. Amine, Lithium Difluoro(oxalato)borate as New Salt for Lithium-Ion Batteries, *Electrochem. Solid-State Lett*., 10(3): A45–A47 (2007)
- Amine, K., Liu, J., and Belharouak, I., High-temperature storage and cycling of C-LiFePO4/graphite Li-ion cells, *Electrochemistry Communications* 7 (7): 669–673 JUL 2005
- Zonghai Chen, Qingzheng Wang, and K. Amine, Understanding the Stability of Aromatic Redox Shuttles for Overcharge Protection of Lithium-Ion Cells*, Journal of the Electrochemical Society*, 153(12): A2215-A2219 (2006).

The following three articles on Li-ion battery chemistry, authored by ANL's Chemical Engineering Division researchers, were cited as among the top 25 downloaded articles from "Science Direct" from July to September, 2005. All three were published in *Electrochemistry Communications*:

- New active titanium oxyphosphate material for lithium batteries, I. Belharouak and K. Amine, Electrochemistry Communications 7(7), 648–651, July 2005.
- High-temperature storage and cycling of C-LiFePO4/graphite Li-ion cells, K. Amine, J. Liu, and I. Belharouak, Electrochemistry Communications 7(7), 669–673, July 2005.
- Synthesis and electrochemical analysis of vapor-deposited carbon-coated LiFePO4, I. Belharouak, C. Johnson, and K. Amine, Electrochemistry Communications 7(10), 983-988, October 2005.

The ANL research manager who was interviewed also identified the following eight ANL patents on new composite-structure electrode materials for rechargeable Li-ion batteries as being particularly important to downstream innovation. The first three are attributed to ANL researchers M. M. Thackeray, C. S. Johnson, K. Amine and J. Kim; and the last are attributed to M. M. Thackeray, K. D. Kepler, and J. T. Vaughey; all are assigned to the University of Chicago:[216]

- U.S. Patent 6,677,082 (2004), *Lithium Metal Oxide Electrodes for Lithium Cells and Batteries* — 5 forward references
- U.S. Patent 6,680,143 (2004), *Lithium Metal Oxide Electrodes for Lithium Cells and Batteries* — 3 forward references
- U.S. Patent 7,135,252 (2006), Lithium Metal Oxide Electrodes for Lithium Cells and Batteries — 0 forward references
- U.S. Patent 6,528,208 (2003) *Anodes for Rechargeable Lithium Batteries* — 4 forward references
- U.S. Patent 7,026,074 (2006), *Lithium Ion Battery with Improved Safety* — 0 forward references

[216] Ibid.

- U.S. Patent 2005/0019670 (2005), *Long Life Lithium Batteries with Stabilized Electrodes* — 0 forward references
- U.S. Patent 2006/0199080 (2006), *Novel Redox Scuttles for Overcharge Protection of Lithium Batteries* — 0 forward references
- U.S. Patent 2005/0058588, *Method and Apparatus for Preparation of Spherical Metal Carbonates and Lithium Metal Oxides for Lithium Rechargeable Batteries* — 0 forward references

ANL's battery research manager also identified additional noteworthy patents and patent applications attributed to ANL researchers in the field of lithium batteries, listed below. Note that the list includes the cathode patents shown above. Among those listed are 19 patent applications that have not yet been granted, and 12 patents that have been granted.

ANL Identified Patents (highlighted) and Patent Applications in the field of lithium batteries (partial list):

Composite Cathode Structures

US Patent 6,677,082 – $xLi_2M'O_3$•$(1-x)LiMO_2$ (M base = Ni; M′ base = Mn)

US Patent 6,680,143 – $xLi_2M'O_3$•$(1-x)LiMO_2$ (M base = Mn)

US Patent 7,135,252 – $xLi_2M'O_3$•$(1-x)LiMO_2$ (CIP)

US Patent Application 20060051673 – $xLi_2M'O_3$•$(1-x)LiM_2O_4$ – layered-spinel (CIP)

US Patent Application 20060051671 – $xLi_2M'O_3$•$(1-x)LiM_2O_4$ – **layered-spinel (PCT)**

US Patent Application 20060188781 – preconditioned electrodes (CIP)

US Patent Application 20060099508 – $xLi_2M'O_3$•$(1-x)LiMO_2$ (CIP)

US Patent Application 20050026040 – **preconditioned electrodes (PCT)**

US Patent Application 20030180616 – Li_2MO_2 components

Related and Other Cathode Materials

US Patent 7,041,414 – Ag_xMnO_2

US Patent Application 20050058588 – F addition and spherical morphology

US Patent Application 20040091779 – F addition

US Patent Application 20040234854 – composition and method

US Patent Application 20040048156 – $Ag_xV_3O_8$

US Patent Application 20040265696 – $LiNiTiPO_4$

Anode Materials

US Patent 6,221,531 – Doped $Li_4Ti_5O_{12}$
US Patent 6,528,208 – Cu_6Sn_5 etc
US Patent 6,730,429 – Cu_6Sn_5 - method
US Patent 6,528,208 – Cu_6Sn_5 etc
US Patent 6,855,460 – Cu_2Sb etc
US Patent Application 20040131941 – $SrLi_2Ti_6O_{14}$

Coated Electrodes

US Patent 7,049,031 – Protective coating for spinel electrodes

US Patent Application 20040191633 – colloidal coatings

US Patent Application 20040157126 – carbon coating method

Electrolytes and Electrolyte Additives

US Patent 7,026,074 – Electrolyte additive

US Patent Application 20050019670

US Patent Application 20040151951

US Patent Application 20030157413

Cell Design

US Patent 6,858,345 – Wound bipolar lithium battery

Cell Packaging

US Patent Application 20020164441

US Patent Application 20050112461

Note: Provided by ANL Battery Technology Department. Patents granted highlighted in red.

C.2 Ovonic Patent Analysis in More Detail

The first- and second-generation patents citing Ovonic US5,348,822 are discussed and illustrated in Chapter 5, Subsection 5.1.5. The table below lists the assignees of the second-generation patents citing the Ovonic patent.

Table C-1 Assignees of Second-Generation Patents Citing Ovonic US5348822

3M Innovative Properties Company
ABSL Power Solutions Ltd.
Affymetrix, Inc.
Alcatel
BERUBE JOHN W.
BYD Battery Co., Ltd.
Canon Kabushiki Kaisha
Cardiac Pacemakers, Inc.
CHAN; CHUNG
Cymbet Corporation
Dowa Mining Co., Ltd.
Duracell Inc.
Eagle-Picher Industries, Inc.
Energy Conversion Devices, Inc.
Energy Science Laboratories, Inc.
Excellatron Solid State, LLC
Ferro GmbH
Furukawa Denchi Kabushiki Kaisha
H. C. Starck GmbH & Co.
HAZELTON PETER D.
Honda Giken Kogyo Kabushiki Kaisha
Infinite Power Solutions, Inc.
International Business Machines Corporation
Japan Storage Battery Co., Ltd.
Johnson Research & Development
Kabushiki Kaisha Toshiba
Korea Advanced Institute of Science & Technology
Levanon; Baruch
LG Electronics Inc.

Matsushita Electric Industrial Co., Ltd.
Merck Patent Gesellschaft Mit Beschrankter Haftung
Moltech Power Systems, Inc.
Morgan Adhesives Company
Motorola, Inc.
Murata Manufacturing Co., Ltd.
Nippaku Sangyo Co., Ltd.
Nippon Foil Mfg. Co., Ltd.
Osram Sylvania Inc.
Ovonic Battery Company, Inc.
Renata AG
Reveo, Inc
RYAN WILLIAM J.
SAFT
Sakai Chemical Industry Co., Ltd.
Samsung Display Devices Co., Ltd.
Sanoh Kogyo Kabushiki Kaisha
Sanyo Electric Co., Ltd.
Sharp Kabushiki Kaisha
Silicon Genesis Corporation
Sony Corporation
Sumitomo Electric Industries, Ltd.
Tanaka Chemical Corporation
The Gillette Company
The Regents of the University of California
Toshiba Battery Co., Ltd.
Toyota Jidosha Kabushiki Kaisha
Wilson Greatbatch Ltd.
Yuasa Corporation

Note that several companies are listed more than once when they are the assignee for more than one second-generation patent.

Appendix D. Patent List in Support of Chapter 6

D.1 List of 71 DOE-Funded Patents Found in the HEV/PHEV/EV Battery/Ultracapacitor Patent File Identified by Applying a Filter

Table D-1 DOE-Funded Patents Also Found within the List of HEV/PHEV/EV Patents

Patent	Issue Year	Assignee	Title
4540639	1985	ExxonMobil Corp	Method and apparatus for maintaining the ph in zinc bromine battery systems
4721513	1988	DOE	Cathode preparation method for molten carbonate fuel cell
4842963	1989	DOE	Zinc electrode and rechargeable zinc air battery
5006424	1991	University of California	Battery using a metal particle bed electrode
5173362	1992	Johnson Controls Inc	Composite substrate for bipolar electrodes
5219679	1993	EIC Laboratories Inc	Solid electrolytes
5252413	1993	EIC Laboratories Inc	Solid polymer electrolyte lithium batteries
5260855	1993	University of California	Supercapacitors based on carbon foams
5314765	1994	Lockheed Martin Corp.	Protective lithium ion conducting ceramic coating for lithium metal anodes and associate method
5336274	1994	University of California	Method for forming a cell separator for use in bipolar stack energy storage devices
5358802	1994	University of California	Doping of carbon foams for use in energy storage devices
5393619	1995	University of California	Cell separator for use in bipolar stack energy storage devices
5402306	1995	University of California	Aquagel electrode separator for use in batteries and supercapacitors
5426006	1995	Lockheed Martin Corp.	Structural micro porous carbon anode for rechargeable lithium ion batteries
5434020	1995	University of California	Continuous feed electrochemical cell with nonpacking particulate electrode
5441820	1995	University of California	Electrically recharged battery employing a packed/spouted bed metal particle electrode
5474860	1995	EIC Laboratories Inc	Solid polymer electrolytes
5484670	1996	Arizona State University	Lithium ion conducting ionic electrolytes
5506073	1996	Arizona State University	Lithium ion conducting electrolytes
5527640	1996	University of California	Electrochemical supercapacitors
5626987	1997	SAFT	Hydridable material for the negative electrode in a nickel-metal hydride storage battery

5636437	1997	University of California	Fabricating solid carbon porous electrodes from powders
5656388	1997	California Institute of Technology	Metal hydrides as electrode/catalyst materials for oxygen evolution/reduction in electrochemical devices
5716736	1998	Midwest Research Institute	Solid lithium-ion electrolyte
5749927	1998	Grace (W.R.) Co.	Continuous process to produce lithium-polymer batteries
5772934	1998	Grace (W.R.) Co.	Process to produce lithium-polymer batteries
5777428	1998	Maxwell Technologies	Aluminum-carbon composite electrode
5834137	1998	Midwest Research Institute	Thin-film method of conducting lithium-ions
5841627	1998	University of Chicago	Pseudo-capacitor device for aqueous electrolytes
5849427	1998	DOE	Hydraulically refueled battery employing a packed bed metal particle electrode
5858573	1999	EIC Laboratories Inc	Chemical overcharge protection of lithium and lithium-ion secondary batteries
5862035	1999	Maxwell Technologies	Multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
5888665	1999	California Institute of Technology	LaNi.sub.5 is based metal hydride electrode in Ni-MH rechargeable cells
5907472	1999	Maxwell Technologies	Multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
5949219	1999	DOE	Optical state-of-charge monitor for batteries
5962169	1999	Arizona State University	Lithium ion conducting electrolytes
5973913	1999	Covalent Associates Inc	Nonaqueous electrical storage device
5986432	1999	Alcatel-Lucent	Method of charging maintenance-free nickel metal hydride storage cells
5989748	1999	DOE	Cyanoethylated compounds as additives in lithium/lithium batteries
5993969	1999	Lockheed Martin Corp.	Carbon film electrodes for super capacitor applications
6007944	1999	Varta Batterie AG	Rechargeable lithium-ion cell
6059847	2000	Maxwell Technologies	Method of making a high performance ultracapacitor
6084766	2000	General Electric Company	Method of making an ultracapacitor electrode
6084767	2000	General Electric Company	Ultracapacitor separator
6094788	2000	Maxwell Technologies	Method of making a multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
6096454	2000	University of California	Surface modifications for carbon lithium intercalation anodes
6110321	2000	General Electric Company	Method for sealing an ultracapacitor, and related articles
6110621	2000	University of Chicago	Carbons for lithium batteries prepared using sepiolite as an inorganic template
6152970	2000	General Electric Company	Drying an ultracapacitor
6168694	2001	Chemat Technology Inc	Methods for and products of processing nanostructure nitride, carbonitride and oxycarbonitride electrode power materials by utilizing sol gel technology for supercapacitor applications
6198620	2001	General Electric Company	Ultracapacitor separator
6201685	2001	General Electric Company	Ultracapacitor current collector

6212061	2001	General Electric Company	Sealing an ultracapacitor
6238823	2001	Brookhaven Science Associates	Non-stoichiometric AB5 alloys for metal hydride electrodes
6242132	2001	UT-Battelle LLC	Silicon-tin oxynitride glassy composition and use as anode for lithium-ion battery
6256190	2001	General Electric Company	Ultracapacitor electrolyte
6304426	2001	General Electric Company	Method of making an ultracapacitor electrode
6356433	2002	University of California	Conducting polymer ultracapacitor
6364915	2002	General Electric Company	Method of sealing an ultracapacitor substantially free of water
6383640	2002	University of California	Conducting polymer for high power ultracapacitor
6451073	2002	Maxwell Technologies	Method of making a multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
6466428	2002	General Electric Company	Ultracapacitor having residual water removed under vacuum
6511517	2003	NBT GmbH	Method for producing a secondary lithium cell comprising a heat-sensitive protective mechanism
6558437	2003	General Electric Company	Method of making an ultracapacitor electrode
6565701	2003	General Electric Company	Ultracapacitor current collector
6583599	2003	Ford Motor Co.	Method and apparatus for controlling battery charging in a hybrid electric vehicle
6858345	2005	University of Chicago	Wound bipolar lithium polymer batteries
6881519	2005	Johnson Controls Inc	Ni/metal hydride secondary element
7012124	2006	Arizona State University	Solid polymeric electrolytes for lithium batteries
7026074	2006	University of Chicago	Lithium ion battery with improved safety
7122261	2006	University of California	Metal hydride fuel storage and method thereof

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