December 2013

Benefit-Cost Evaluation of U.S. DOE Investment in Energy Storage Technologies for Hybrid and Electric Cars and Trucks

Final Report

Prepared for

Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
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Washington, DC 20585

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Executive Summary

This benefit-cost evaluation analyzes the Vehicle Technology Office's (VTO's)[1] research and development investments in energy storage technologies for hybrid and electric cars and light-duty trucks. Specifically, it compares investments (costs) with the social benefits accruing from VTO investments in nickel metal hydride (NiMH) and lithium ion (Li-ion) battery technologies—the two chemistry families that power all hybrid and electric cars and trucks on the road today.

In consideration of the growth in market adoption of EDVs, this evaluation answers the question of whether VTO's investments contributed to this adoption, and if so, what has been VTO's return on its investments in vehicle energy storage R&D.

Advancing battery technologies for electric-drive vehicles (EDVs)—an umbrella term for hybrid (e.g., Ford Fusion), plug-in hybrid (e.g., Chevrolet Volt), and all-electric (e.g., Tesla Model S) vehicles—has been a DOE priority since the passage of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. This analysis concentrates on NiMH and Li-ion battery technologies, which VTO began supporting in 1992, 7 years before the 1999 introduction of the first mass-produced hybrid gasoline-electric cars to the U.S. market.

VTO's research and development (R&D) program was motivated by a congressional mandate to encourage and accelerate technology development that could meet fuel savings, emissions reduction, and energy security goals. VTO's total investment for NiMH, Li-ion, and other energy storage technology development was $971 million[2] from 1992 through 2012.

In 2012, 488,000 electric-drive cars and trucks were sold. In consideration of the growth in market adoption of EDVs, this evaluation answers the question of whether VTO's investments

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[1] VTO is an office in the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE).

[2] Except where noted, all dollar values in this report are presented in real 2012 terms as noted by the term *(2012$)*.

contributed to this adoption, and if so, what has been VTO's return on its investment in vehicle energy storage R&D.

VTO's total investment for NiMH, Li-ion, and other energy storage technology development was $971 million from 1992 through 2012.

Four categories of impacts (energy and resource, environmental, energy security, and knowledge) were quantified. The analysis employed a portfolio approach in which benefits for a subset of technology investments were compared with a more comprehensive cost basis.[3] As such, it provides a lower-bound measure of VTO's return on its $971 million investment. In all, 54 experts in vehicle energy storage technologies participated in this evaluation, representing VTO-funded battery companies, car companies, research laboratories, and universities.

ES.1 ENERGY AND RESOURCE BENEFITS

The principal source of EDVs' energy and resource benefits is EDVs' ability to operate under electric power for some or all of the time. Whereas the average internal combustion vehicle's (ICV's) fuel economy is 23.5 miles per gallon (mpg), the equivalent is 34.8 mpg for hybrids, 40.8 mpg equivalent for plug-in hybrids, and 82.3 mpg equivalent for electric vehicles.[4]

VTO was found to have accelerated the pace of technology development by about 6 years, and in the absence of its support and investment, the state-of-the-art technical performance characteristics of the typical battery that powers an EDV today would be a fraction of what they currently are.

VTO was found to have accelerated the pace of technology development by about 6 years, and in the absence of its support and investment, the state-of-the-art technical performance characteristics of the typical battery that powers an EDV today would be a fraction of what they currently are (see Table ES-1). Battery executives noted that fewer EDVs would have been sold and that some vehicle models would not have been viable as EDVs under these circumstances.

With respect to NiMH technology, one interviewee noted that "without DOE, there would be essentially no U.S. [energy storage] industry. Technology would still have been developed abroad in, for example, Japan and Korea, and EDVs would still have made their way into the U.S. market, but it would have taken longer." Another interviewee noted that VTO's impact on Li-ion technology was still greater: "It is possible that without the [VTO's] support for battery technology development, there might presently be no Li-ion technology in the EDV market."

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[3] VTO's $971 million also included R&D investments for ultracapacitors, flywheels, and measurement infrastructure, for example.
[4] See Huo, Wu, and Wang (2009) and Table 5-13 of this report.

Table ES-1. Battery Life, Energy Density, Cost, and Li-ion EDV Sales Improvements Resulting from VTO's R&D Investments

Metric	Mean
Number of years by which industry-wide R&D was accelerated by VTO	6.1 years
Percentage of progress from 1998 to 2012 resulting from VTO investments	
Battery life	35%
Energy density—NiMH	33%
Cost—NiMH	30%
Energy density—Li-ion	33%
Cost—Li-ion	33%
Percentage of Li-ion vehicle sales resulting from technological improvements funded by VTO	64%

Inferior technical characteristics in the absence of VTO's R&D investments would have meant that substantially fewer EDVs would be on the road (see Figure ES-1). Ultimately, about half of all EDVs sold between 1999 and 2012 were deemed by industry experts and VTO-funded researchers to have resulted from accelerated technological progress funded by VTO; conventional cars and trucks would have been on the road instead of those EDVs.

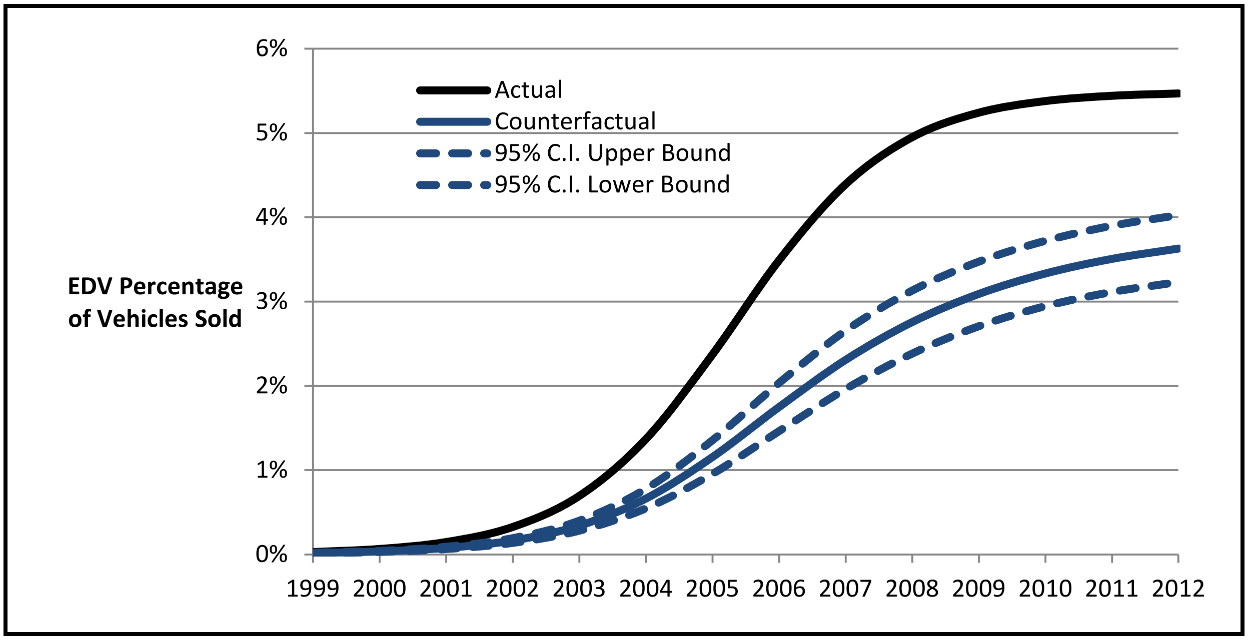
Given typical American driving patterns, this translates into the following:

From 1999 through 2022, savings of 2.1 billion gallons of gasoline valued at $7.3 billion resulted from VTO's investments; new EDVs on the road by the end of 2012 are expected to remain on the road until as late as the end of 2022.

- From 1999 through 2012, savings of 1.0 billion gallons of gasoline, valued at $3.3 billion.
- From 1999 through 2022, savings of 2.1 billion gallons of gasoline valued at $7.3 billion (new EDVs on the road by the end of 2012 are expected to remain on the road until the end of 2022).

These savings were estimated by a model that quantified fuel savings relative to ICVs driving the same distance. Model inputs included expert opinion about EDV adoption in light of batteries' counterfactual technical performance and data for fuel economy, effective useful life, annual numbers of miles driven by vehicle age, and gasoline prices.

Figure ES-1. Counterfactual Market Adoption of EDVs in the United States without Technological Performance Improvements Funded by VTO's R&D Investments



Note: C.I. is confidence interval. Figure is stylized based on total EDV sales through 2011.

ES.2 ENVIRONMENTAL BENEFITS

Under the operation of a conventional gasoline internal combustion engine, vehicles emit a number of pollutants that contribute to air pollution, acid rain, visibility impairment, surface water pollution, and climate change.

VTO's contribution to greenhouse gas reduction through energy storage R&D is estimated to be[5]

- 7.0 million metric tons of CO_2equivalents from 1999 through 2012 and
- 14.5 million metric tons of CO_2equivalents from 1999 through 2022, which is equivalent to eliminating the annual CO_2 emissions of 4.1 coal-fired power plants.[6]

In addition to reduced greenhouse gas emissions, pollutants like volatile organic compounds, nitrous oxides, particulate matter, sulfur dioxide, and ammonia are also reduced. These

[5] The emissions reduction potential described in this summary is on a pump-to-wheels basis; a well-to-wheels emissions reduction analysis is provided as an appendix to the main report.

[6] See the U.S. EPA Greenhouse Gas Equivalency Calculator (EPA, 2012b).

pollutants have a deleterious impact on human health, and the avoidance of their emission adds an additional stream of economic benefits:

- $157 million in environmental health benefits from 1999 through 2012 and
- $341 million in environmental health benefits from 1999 through 2022.

ES.3 ENERGY SECURITY BENEFITS

Avoided fuel combustion can lead to a reduced requirement for foreign oil importation, which may lessen the risk of oil disruptions and exogenous price shocks. Fuel savings were converted into barrels of oil, and the amount of that oil that would have been imported was estimated to be

- 27.2 million barrels of foreign oil importation from 1999 through 2012 and
- 47.8 million barrels of foreign oil importation from 1999 through 2022.

ES.4 KNOWLEDGE BENEFITS

VTO-funded research contributed to the knowledge base in energy storage, as indicated by the issue of 112 patent families in energy storage, consisting of 56 Li-ion battery patent families, 9 NiMH patent families, and 47 ultracapacitor patent families over the period 1976 to 2012 and as indicated by more than 2,337 publications/presentations from 2000 through 2012.[7]

Although the output of patents comprises a small share of global patenting in energy storage, VTO research has formed a particularly influential foundation for subsequent advances in the field. This finding lends supporting evidence to the study's conclusion that a share of the technical advances is attributable to VTO's investment.

When rated in terms of the average number of citations per patent family (to adjust for patent portfolio size differences), VTO ranked first against the leading companies. Furthermore, a

[7] Knowledge impact analysis was contributed by Rosalie Ruegg of TIA Consulting, Inc. and Patrick Thomas of 1790 Analytics, Inc. independently of RTI.

sizable share of company patents linked back to VTO-attributed patents, indicating that commercial companies were using results of VTO's research in energy storage. The intellectual capital developed with VTO funding was also found to have a broad influence on knowledge spillovers in multiple application areas.

ES.5 OVERALL ECONOMIC PERFORMANCE MEASURES

VTO's R&D investments in energy storage technologies for electric and hybrid cars and trucks have been socially valuable. Benefits quantified in this evaluation accrued from fuel savings from increased market adoption and diffusion of EDVs resulting from accelerated technological progress in vehicle energy storage technologies from VTO-funded R&D.

For the period from 1999 through 2012, total economic benefits were $3.4 billion. When compared with the VTO R&D portfolio cost of $971 million through 2012, the economic performance measures are

The benefit-cost ratio is 3.63 to 1, meaning that for every $1 VTO invested, $3.63 is returned, over the lifetime of vehicles sold by the end of 2012. This equates to an average annual rate of return of 17.7% for the 20-year period from 1992 through 2012.

- net present value (NPV)—$506 million, discounted at 7%;
- benefit-cost ratio (BCR)—2.03-to-1, discounted at 7%; and
- internal rate of return (IRR)—14.3%.

However, these performance measures do not account for the fact that the vehicles in the fuel savings analysis have useful lives of 11 years, on average, and therefore are expected to remain on the road until 2022.

When accounting for remaining effective useful life through 2022, total economic benefits increase to $7.6 billion, and the performance measures are

- NPV—$1,294 million, discounted at 7%;
- BCR—3.63-to-1, discounted at 7%; and
- IRR—17.7% (Table ES-2).

Table ES-3 summarizes measures and metrics that report the return on VTO's investments in energy storage along economic, energy, environmental, energy security, and knowledge creation lines.

Table ES-2. Economic Performance Measures, Effective Useful Life Analysis (Benefits Period of 1992-2022)

Measure	Result	Sensitivity Analysis: Scenario 1 (Lower Bound)	Sensitivity Analysis: Scenario 2 (Upper Bound)
Net present value (millions 2012$, 7% discount rate)	1,294	1,025	1,564
Benefit-to-cost ratio (7% discount rate)	3.63	3.08	4.18
Internal rate of return	17.7	16.4%	18.8%

ES.6 SENSITIVITY ANALYSIS

The performance measures for the effective useful life analysis were recalculated under two sensitivity analysis scenarios:

- *Scenario 1 (Lower Bound).* Each year's estimate of the incremental increase in the market adoption of EDVs was reduced by 1.65 times its standard deviation. This sensitivity adjustment results in a lower-bound estimate below which the true value would be expected to occur only 5% of the time.
- *Scenario 2 (Upper Bound)*. Each year's estimate of the incremental increase in the market adoption of EDVs was increased by 1.65 times its standard deviation. This sensitivity adjustment results in an upper-bound estimate above which the true value would be expected to occur only 5% of the time.

In the lower bound scenario, the BCR is 3.08; VTO's investment in energy storage R&D has clearly been socially beneficial.

ES.7 CONSERVATE NATURE OF REPORTED RESULTS

The return on investment metrics we report should be interpreted as lower-bound estimates for several reasons.

- Benefits were not calculated for other VTO energy storage technologies, though their costs were included.
- Only vehicles on the road before January 1, 2013, were included in the benefit-cost analysis; vehicles entering operation on or after this date will certainly contain technology supported by VTO.

Table ES-3. Summary Benefit-Cost Analysis Results

	Benefits Period		
	Retrospective (1999–2012)	**Useful Life (1999–2022)**	**Unit of Measure**
Summary Measures of Economic Performance			
Total benefits	$3,433	$7,650	Million, 2012$
Total VTO investment costs through 2012	$971	$971	Million, 2012$
Net benefits	$2,462	$6,679	Million, 2012$
Net present value @ 7% [Base year = 1992]	$506	$1,294	Million, 2012$
Net present value @ 3% [Base year = 1992]	$1,303	$3,334	Million, 2012$
Benefit-to-cost ratio @ 7% real discount rate	2.03	3.63	
Benefit-to-cost ratio @ 3% real discount rate	2.85	5.74	
Internal rate of return (annual)	14.3%	17.7%	
Energy and Resource Benefits			
Fuel savings (gasoline)	1,029,784	2,125,539	Thousand gallons
Value of fuel savings	$3,276	$7,308	Million, 2012$
Environmental Benefits[a]			
Avoided GHG emissions (CO_2eq)	6,989,237	14,461,042	Metric tons
Avoided volatile organic compounds emissions (VOCs)	3,928	7,926	Short tons
Avoided nitrogen oxides (NO_x)	1,217	2,324	Short tons
Avoided particulate matter emissions ($PM_{2.5}$)	2	16	Short tons
Avoided sulfur dioxide emissions (SO_2)	128	265	Short tons
Avoided ammonia emissions (NH_3)	643	1,329	Short tons
Mean value of environmental health benefits @ 7%	$157	$341	Millions, 2012$
Mean value of environmental health benefits @ 3%	$176	$383	Millions, 2012$
Energy Security Benefits			
Avoided petroleum consumption	54,199,182	111,870,462	Barrels of oil
Avoided foreign petroleum consumption	27,226,445	47,833,782	Barrels of oil
Knowledge Benefits			
DOE-attributed patent families in energy storage	112	N/A	Patent families
DOE publications in batteries	2,337	N/A	Publications

[a] Environmental benefits were quantified using pump-to-wheels emissions factors.

- VTO's return on investment in Li-ion is expected to be greater than VTO's return on investment in NiMH, yet only 2 years of market adoption of Li-ion–powered vehicles are included in the benefits estimation. Experts participating in the evaluation predict the availability of new models in multiple vehicle segments and increasing adoption of Li-ion–powered EDVs over the next 5 years.
- Newer cars and trucks may in actuality have effective useful lives longer than the average of 11 years documented in federal statistics.
- EDVs' greater adoption in urban areas may have environmental benefits greater than what were estimated at the national level.

1 Introduction

This benefit-cost analysis evaluates the social benefits of the Department of Energy's (DOE) Vehicle Technologies Office's (VTO's) research and development investments in nickel metal hydride (NiMH) and lithium-ion (Li-ion) energy storage technologies (hereafter battery technologies) for passenger cars and light-duty trucks from 1992 through 2012.[8]

This benefit-cost analysis evaluates the social benefits of VTO's R&D investments in NiMH and Li-ion energy storage technologies (hereafter battery technologies) for passenger cars and light-duty trucks from 1992 through 2012.

NiMH and Li-ion are the two principal energy storage technology families that power hybrid, plug-in hybrid, and all-electric vehicles on American roads today. These technologies were, and continue to be, a principal focus of VTO's research and development (R&D) portfolio.[9] In 2012, 488,000 of all new passenger car and light-duty truck sales were electric-drive vehicles (EDVs).

In consideration of the growth in market adoption of hybrid and all-electric vehicles, this evaluation answers the question of whether VTO's investments contributed to this adoption, and if so, what has been VTO's return on its investments in vehicle energy storage R&D.

Energy storage technology development is an essential element of VTO's mission:

- Energy storage technologies, especially batteries, are critical enabling technologies for developing advanced,

[8] Although the focus of this evaluation is on new cars and light-duty trucks, much of VTO-sponsored R&D will transfer to energy storage for heavy-duty hybrid vehicles as well.

[9] VTO is in the Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). VTO activities that are not included in this evaluation are Hybrid and Vehicle Systems, Power Electronics and Electrical Machines, Advanced Combustion Engines, Fuels and Lubricants, Materials Technologies, Analysis and Tools, Energy Policy Act (EPAct) Transportation Regulatory Activities, Clean Cities, and Research Partnerships.

fuel-efficient, light- and heavy-duty vehicles, which are key components of DOE's Energy Strategic Goal: "to protect our national and economic security by promoting a diverse supply and delivery of reliable, affordable, and environmentally sound energy."

- VTO supports the development of durable and affordable advanced batteries covering the full range of vehicle applications, from start/stop to full-power hybrid electric, plug-in hybrid electric, electric, and fuel cell vehicles.
- Energy storage research aims to overcome specific technical barriers that have been identified by the automotive industry together with VTO—cost, performance, life, and abuse tolerance. These barriers are being addressed collaboratively by DOE's technical research teams and battery manufacturers.

VTO invested $971 million in energy storage R&D from 1992 through 2012. Thus, 83% of VTO's real R&D investments in energy storage technologies are being evaluated in this study.

VTO invested more than $1,168 million in real, 2012 dollars in energy storage R&D between 1976 and 2012, of which $971 million was made from 1992 through 2012.[10] (All dollar values in this report are presented in real 2012, except where noted.) Thus, 83% of VTO's R&D investments in energy storage technologies (referred to as VTO's R&D investments) are evaluated in this study.

Benefits were quantified for two periods—1992 through 2012 and 1992 through 2022 (because a typical vehicle has an 11-year useful life[11])—and compared with 1992 through 2012 investment costs.

Four categories of impacts are considered, although not all are expressed in dollar terms:

1. energy and resource,
2. environmental,

[10] In nominal dollar terms the amount was $917 million. The nominal R&D investment dollars were converted to 2012 dollars using the gross domestic product (GDP) chain-type price index as constructed by the U.S. Department of Commerce, Bureau of Economic Analysis. See Appendix B.

[11] The average vehicle on the road by 2012 will remain on the road beyond the retrospective period of analysis (1992 through 2012). Therefore, we include an effective useful life analysis (1992 through 2022) in which DOE investments are compared with benefits for the combined retrospective period and the period covering the remaining effective useful life for vehicles on the road as of December 31, 2012.

3. energy security, and
4. knowledge.

Only impacts resulting directly from VTO's support of and investment in NiMH and Li-ion battery technologies were considered.

The remainder of this report is organized as follows:

- Section 2 presents VTO's R&D investments in energy storage technologies over time.
- Section 3 focuses on the diffusion of NiMH and Li-ion battery technologies over time both in the aggregate and with respect to specific models of EDVs—an umbrella term that describes all types of EDVs, including hybrid electric vehicles (HEVs), electric vehicles (EVs), and plug-in hybrid electric vehicles (PHEVs).
- Section 4 reviews the methodology used to consider four categories of impacts: energy and resource, environmental, energy security, and knowledge benefits.
- Section 5 quantifies the energy and resource benefits measured in this study, specifically the economic value of fuel savings associated with the adoption over time of NiMH and Li-ion battery technologies in EDVs.
- Section 6 quantifies the environmental and energy security benefits measured in this study, including the economic value of avoided adverse health incidence related to emissions reductions.
- Section 7 discusses the knowledge benefits traceable to VTO's R&D investments.
- Section 8 presents a comparison of monetized benefits for 1999 through 2012 associated with NiMH and Li-ion battery technologies with VTO's R&D investments from 1992 through 2012.
- Section 9 extends the calculation of monetized benefits to include benefits that will accrue during the remaining effective useful life of EDVs purchased before the end of 2012. These so-called life-cycle benefits are also compared with VTO's R&D investments for 1992 through 2012.
- Section 10 concludes the study with a summary of the findings.

2 VTO R&D Investments in Energy Storage Technologies

Between 1992 and 2012, VTO invested $971 million (2012$) in energy storage R&D, only a portion of which was for NiMH and Li-ion battery technologies. This section offers an abbreviated history of DOE funding for energy storage R&D for vehicles. It also provides a timeline of VTO's R&D investments specifically for NiMH and Li-ion technologies beginning in 1992.

2.1 GENESIS OF DOE FUNDING FOR ELECTRIC-DRIVE VEHICLES

As the nation realized the importance of expanded R&D in alternative forms of energy following the energy crisis of the early 1970s, the Atomic Energy Commission was replaced by the Energy Research and Development Administration (ERDA) in an effort to unify the federal government's energy R&D.[12] Congress charged ERDA to sponsor R&D related to electric and hybrid vehicles through the passage of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, Public Law 94-413. Therein:[13]

> *The Congress finds and declares that—*
>
> *(1) the Nation's dependence on foreign sources of petroleum must be reduced, as such dependence jeopardizes national security, inhibits foreign policy, and undermines economic well-being;*

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[12] On August 4, 1977, President Carter signed the Department of Energy Reorganization Act of 1977, Public Law 95-91, transferring the mission of ERDA to the newly formed DOE'.

[13] For more information, see: http://uscode.house.gov/download/pls/15C52.txt.

(2) the Nation's balance of payments is threatened by the need to import oil for the production of liquid fuel for gasoline-powered vehicles;

(3) the single largest use of petroleum supplies is in the field of transportation, for gasoline- and diesel-powered motor vehicles;

(4) the expeditious introduction of electric and hybrid vehicles into the Nation's transportation fleet would substantially reduce such use and dependence; …

Congress charged ERDA (DOE's predecessor) to sponsor R&D related to electric and hybrid vehicles through the passage of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976.

In early 1991, Chrysler (now Chrysler Group LLC), Ford Motor Company, and General Motors (GM) established the U.S. Advanced Battery Consortium (USABC) to accelerate the development of batteries for EDVs. The USABC was motivated, in part, by the California Air Resources Board's 1990 regulations for low-emission vehicles and its clean fuel standards for emissions that applied to new classes of vehicles by 1994.

The purpose of the USABC was to "work with advanced battery developers and companies that will conduct research and development (R&D) on advanced batteries to provide increased range and improved performance for electric vehicles in the latter part of the 1990s" (NRC, 1998, p. 12). More specifically, the USABC had the following overarching objectives:

- to establish a capability for an advanced battery manufacturing industry in the United States,
- to accelerate the market potential of EVs [electric vehicles] through joint research on the most promising advanced battery alternatives,
- to develop electrical energy systems capable of providing EVs with ranges and performance levels competitive with petroleum-based vehicles, and
- to leverage external funding for high-risk, high-cost R&D on advanced batteries for EVs.

DOE joined the consortium in late 1991 in response to its mandate through the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976.[14] And, this

[14] It is beyond the scope of this report to explore the extent to which there was an underinvestment in battery energy storage technology by the private sector as justification for public-sector support.

mandate was reconfirmed through the Energy Policy Act of 1992 (EPAct).[15]

Related to the ongoing charge for DOE's involvement in electric and hybrid vehicles and related battery research, President Clinton initiated the Partnership for a New Generation of Vehicles (PNGV) program in 1993. This was a cooperative R&D program between the federal government and the U.S. Council for Automotive Research, which included Chrysler, Ford, GM, and relevant federal agencies and national laboratories (Sissine, 1996). Noteworthy was one of the original technology goals of PNGV (Sissine, 1996):

The purpose of the U.S. Advanced Battery Consortium was to "work with advanced battery developers and companies that will conduct R&D on advanced batteries to provide increased range and improved performance for electric vehicles in the latter part of the 1990s."

> *Research that could lead to production prototypes of vehicles capable of up to three times greater fuel efficiency. Examples would be light-weight materials for body parts and the use of fuel cells and advanced energy storage systems such as ultracapacitors. Using these new power sources would produce more fuel-efficient cars.*

A more fuel-efficient car might achieve a stated goal of 80 miles per gallon (mpg). An Office of Technology Assessment (OTA) report stated in 1995 that there was at that time no battery technology capable of achieving the equivalent of 80 mpg. However, the report went on to state that "Nickel metal-hydride batteries are seen as the only longer-term battery technology that could possibly be designed to reach the 80 mpg target" (OTA, 1995, p. 17).[16]

Funding from VTO for battery research for NiMH and Li-ion technologies began in 1990, although DOE had invested in general energy storage research since 1976. In 1991, DOE made its first allocation to USABC in the amount of $6.4 million (NRC, 1998, p. 17) and provided funding to USABC in each subsequent year.

In addition to the consortium itself and the synergies that logically followed, the USABC established what became the standardized performance metrics for batteries (Table 2-1).

[15] EPAct reaffirmed this mandate and authorized the Secretary of Energy to join cooperative agreements with industry to develop advanced batteries for EDVs (NRC, 1998).

[16] The PNGV's progress in battery technology is reviewed in NRC (2001).

Table 2-1. Performance Metrics Established by USABC

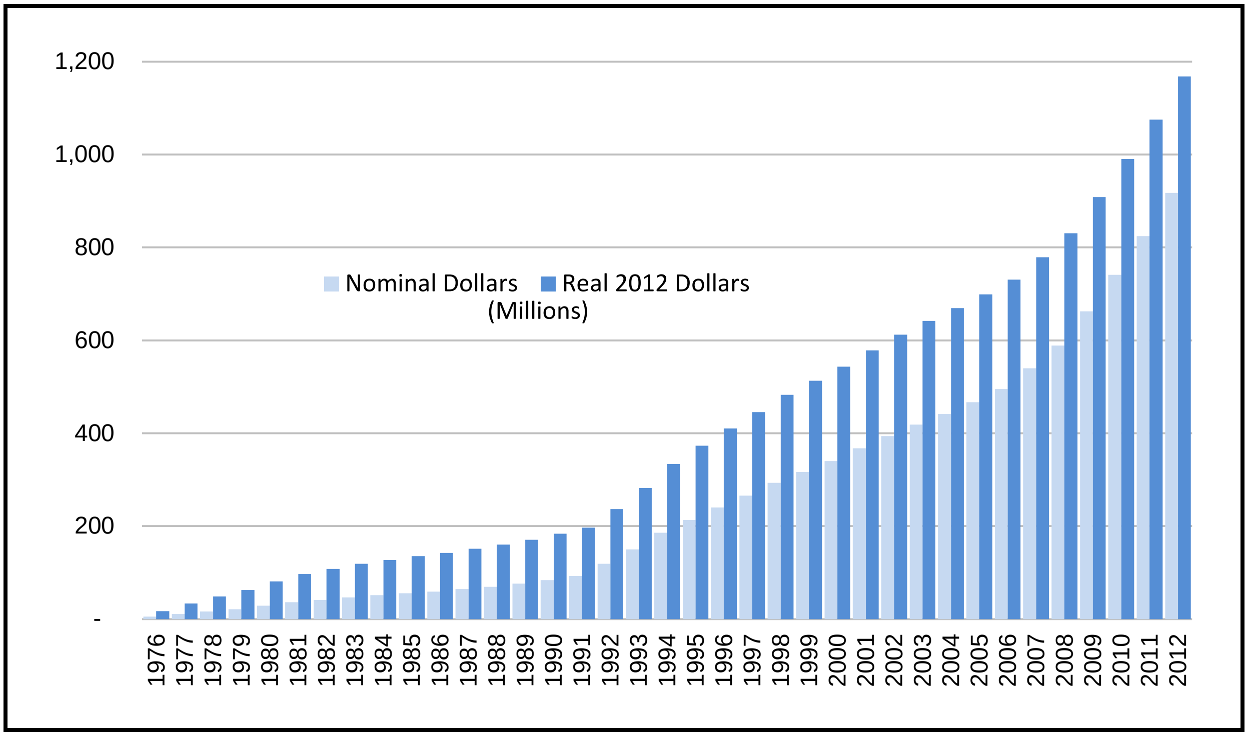
Metric	Definition
Specific energy (Wh/kg)	A measure of the total energy density of the battery pack per unit weight. It provides an indication of the vehicle range. Total energy is analogous to the size of the gas tank on a conventional, combustion-engine powered automobile. This metric is important for EV batteries because added mass requires more energy to move.
Energy density (Wh/L)	A measure of the total energy stored in the battery pack per unit volume. This metric is important in portable electronics where size is often limited.
Specific power (W/kg)	A measure of the total power that can be delivered per unit weight. Power, which is energy divided by the time it is delivered, translates to the acceleration ability of the source. In EVs, power is limited by how fast the energy in a battery pack can be delivered to motors or electrical circuitry.
Power density (W/L)	A measure of the total power per unit volume of the battery pack that can be delivered in a short burst of time such as during acceleration.
Life (years)	An engineering estimate of the expected time that an EV battery pack can be fully charged and discharged and maintain a specified capacity threshold. Some degradation in the pack's specific energy occurs over time, and the battery needs to be replaced when its capacity falls below a specified percentage of the original value.
Cycle life (cycles)	The number of times a battery pack can be charged and discharged. Each charge-discharge event constitutes one cycle. Typically cycle life is related to the depth of discharge (DOD) of the battery pack. Deep discharge and charge cycles will lower cycle life.
Ultimate price ($/kWh)	The cost of a battery pack in dollars divided by the total energy that is contained (in kWh) in a single charge of the battery.
Operating environment	The environmental conditions under which the battery pack is expected to operate. The operating environment usually consists of a lower temperature limit and an upper temperature limit. Batteries typically do not operate at extreme cold conditions and may exhibit reduced performance or become unsafe at high temperatures.
Capacity	The total energy stored in the battery, usually expressed in kWh.
Recharge time (hours)	The time that it takes to recharge the battery to a predetermined acceptable level. Recharge time is often expressed as C rate. A recharge rate of 1C implies that the full capacity of the battery can be restored after 1 hour of charging, whereas a recharge rate of 0.1C implies that it takes roughly 10 hours to fully charge the battery pack.
Continuous discharge in 1 hour	Energy delivered in a constant power discharge required by an EV for hill climbing and high-speed cruising, specified as the percentage of energy capacity delivered in a 1-hour constant power discharge.
Power and capacity degradation	Performance degradation defines the extent to which the battery system is unable to meet the original performance specification.

See Appendix A.

2.2 CUMULATIVE VTO R&D INVESTMENTS IN ENERGY STORAGE TECHNOLOGY

Between 1976 and 2012, VTO's R&D investments in energy storage technology totaled $1,168 million (2012$), as illustrated in Figure 2-1.

Figure 2-1. Cumulative VTO R&D Investments, 1976–2012



Note: The data underlying Figure 2-1 are presented in Table B-1 in Appendix B. Investment data were provided by DOE and adjusted using the GDP chain-type price index from U.S. Department of Commerce, Bureau of Economic Analysis.

This evaluation covers the period from 1992 through 2012. The aforementioned $971 million invested from 1992 through 2012 included all VTO support for NiMH and Li-ion battery technologies, and it is these investments, discounted to January 1, 1992, that comprise the cost basis for the economic performance measures calculated in this evaluation.[17]

However, not all of the $971 million of VTO's R&D investments in energy storage technologies after 1992 were directed toward NiMH and Li-ion battery technologies. Other funded projects were for ultracapacitors, flywheels, test methods and standards, and other energy storage technologies. Thus, to anticipate a point to be made in Section 8, VTO's R&D investments associated with the quantified social benefits presented in Sections 5 and 6 *overstate* the actual R&D investment cost in those technologies. Accordingly, the

[17] The funding for 1976 through 1991, which amounted to $197 million (2012$), supported general energy storage technologies, including various battery chemistries, flywheels, ultracapacitors, and testing methods and standards.

economic performance measures in Sections 8 and 9 *understate*, and are therefore lower bounds of, the true social impact of VTO's R&D investments.

2.3 VTO R&D INVESTMENTS THROUGH THE U.S. ADVANCED BATTERY CONSORTIUM

Important mechanisms of VTO support for NiMH and Li-ion battery technology were USABC contracts to private-sector companies, which began around 1995. These contracts were awarded through a competitive process.

Important mechanisms of VTO support for NiMH and Li-ion battery technology were USABC contracts to private-sector companies, which began around 1995. These contracts were awarded through a competitive process and were managed by VTO's predecessor, the Office of Transportation Technologies (OTT).[18] The OTT also managed Cooperative Research and Development Agreements (CRADAs) with DOE's national laboratories. These CRADAs often focused on developing test procedures and evaluating batteries developed through the USABC program.

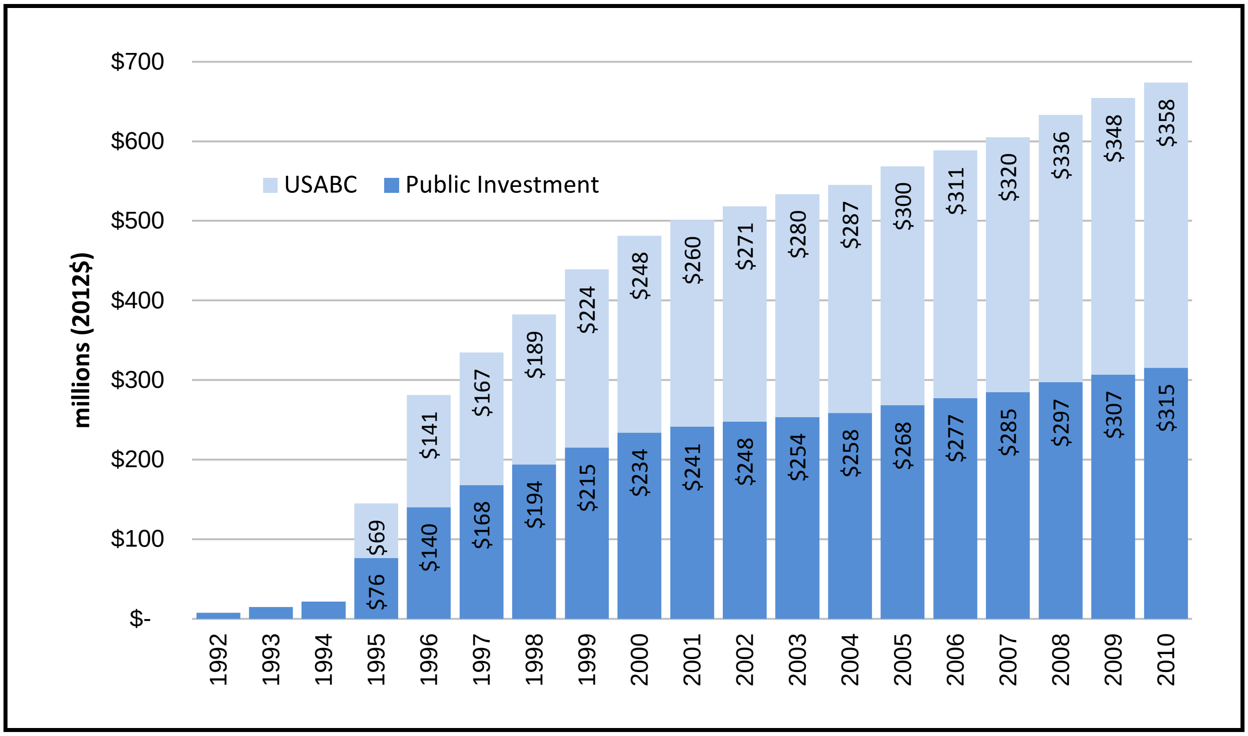
As illustrated in Figure 2-2, VTO channeled $315 million (2012$) in funding via USABC contracts between 1992 and 2010, the latest year for which USABC contract data are available. Private-sector R&D investment amounted to an additional $358 million over the same period.

Approximately 9% of VTO's USABC cumulative investments supported NiMH battery research. U.S. companies receiving support for NiMH R&D included

- Energy Conversion Devices, Inc. (ECD), also known as ECD Ovonic;
- Ovonic Battery Company, Inc., a subsidiary of ECD Ovonic;
- GM Ovonic, a joint venture between GM and Ovonic Battery Company;
- Texaco Ovonic Battery Systems, a joint venture between Texaco and Ovonic Battery Company (Texaco acquired GM's interest); and
- Cobasys LLC, a joint venture between Chevron and Ovonic Battery Company (Chevron acquired Texaco's interest) (see Figure 2-3).

[18] See NRC (1998) for a discussion about how contracts were awarded.

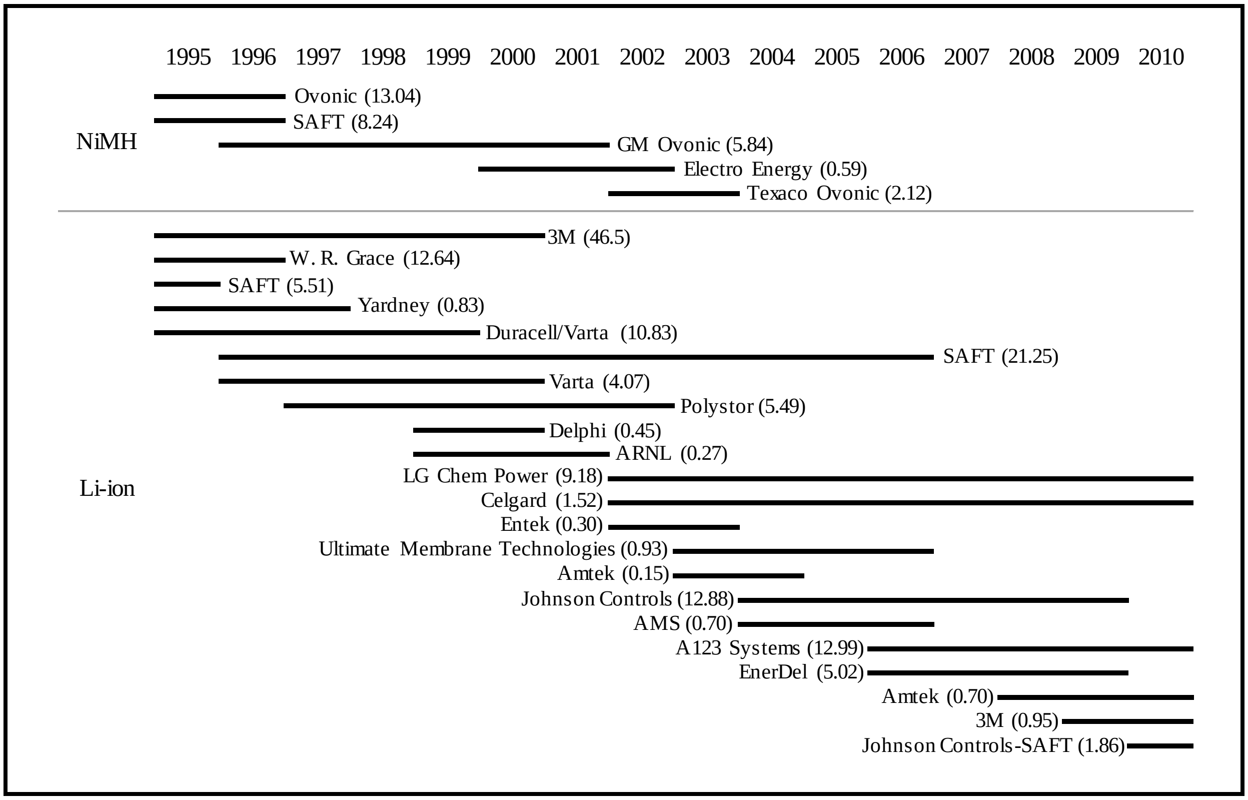
Figure 2-2. Cumulative USABC R&D Investments in Energy Storage Technologies, 1992–2010



Approximately 50% of VTO's USABC cumulative investments supported Li-ion battery research. U.S. companies receiving support for Li-ion battery research included

- 3M;
- Johnson Controls;
- Saft;
- Johnson Controls/Saft (JCS), a joint venture between Johnson Controls and Saft;
- A123Systems;
- LG Chem Power Inc., a North American subsidiary of LG Chem Ltd (see Figure 2-3).

Figure 2-3. VTO R&D Investments for NiMH and Li-ion Battery Technology R&D through the USABC, by Company, 1995–2010 (Millions $)



Note: Figure 2-3 is a timeline of significant (over $0.1 million) VTO funding of USABC contracts. Values appearing in parentheses after company names reflect the total nominal investments of VTO funds in millions of dollars through USABC contracts. USABC data are not available from 1992 to 1995 or after 2010.

Source: DOE archival documents.

3 Market Adoption of NiMH- and Li-ion–Powered Vehicles

Advancements in NiMH and Li-ion battery technologies—improvements in the performance characteristics of the state-of-the-art battery technology—have translated into the commercial availability of EDVs. This section summarizes the market adoption of NiMH and Li-ion battery technologies through the purchase of EDVs in the United States beginning in 1999.

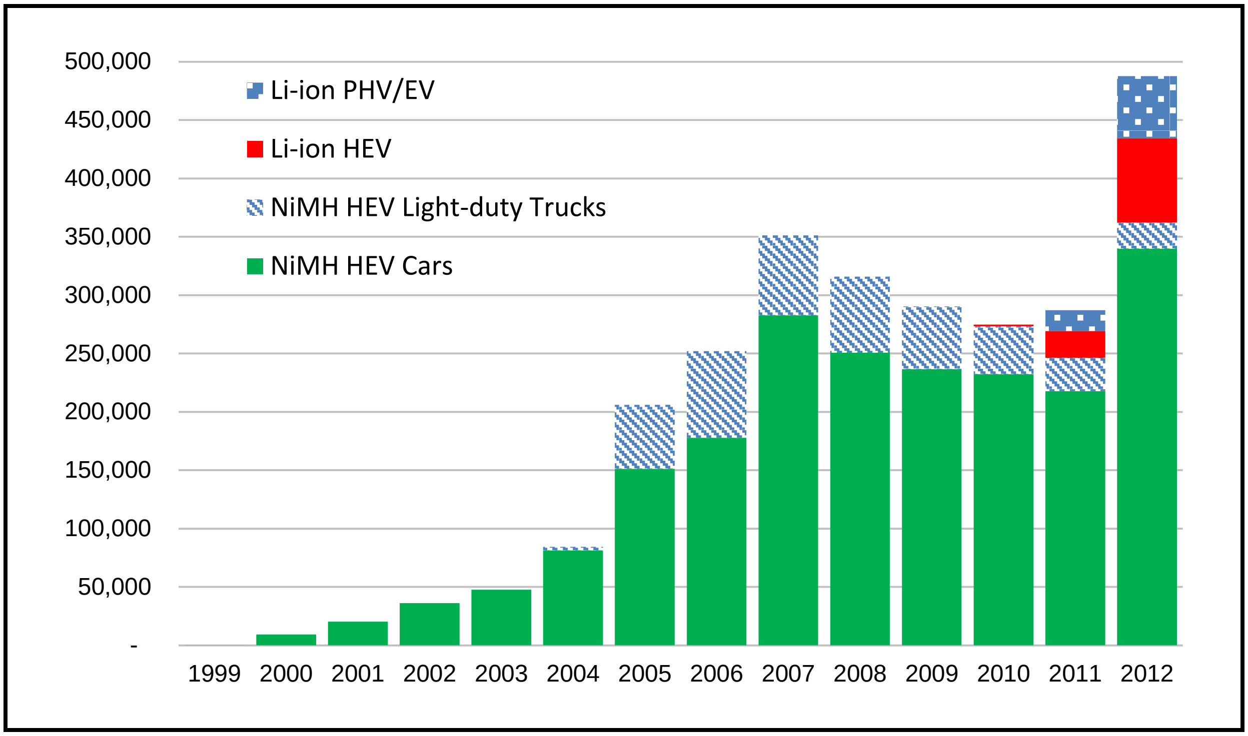
The umbrella term EDVs *describes all types of electric-drive vehicles, including hybrid electric vehicles (HEVs), electric vehicles (EVs), and plug-in hybrid electric vehicles (PHEVs).*

In this evaluation, the umbrella term *EDVs* describes all types of electric drive vehicles, including

- hybrid electric vehicles (HEVs), which use gasoline to charge the battery and part of the time to power the vehicle (e.g., the first-generation Prius);
- electric vehicles (EVs), which are powered exclusively by a battery and must be plugged into an electrical outlet to recharge (e.g., the Tesla Model S, Nissan Leaf); and
- plug-in hybrid electric vehicles (PHEV), which can either use gasoline to recharge the battery and power the vehicle or be plugged in to recharge the battery (e.g., the Chevrolet Volt).

In the United States, it took 9 years to sell the first 1 million EDVs, less than 4 years to sell the next 1 million, and less than 2 additional years to reach a cumulative sales total of 2.66 million. In 2012 alone, 488,000 EDVs were sold. Figure 3-1 shows yearly U.S. sales by vehicle type.

Figure 3-1. Electric Drive Vehicle Sales in the United States, by Battery Technology and EDV Type, 1999–2012



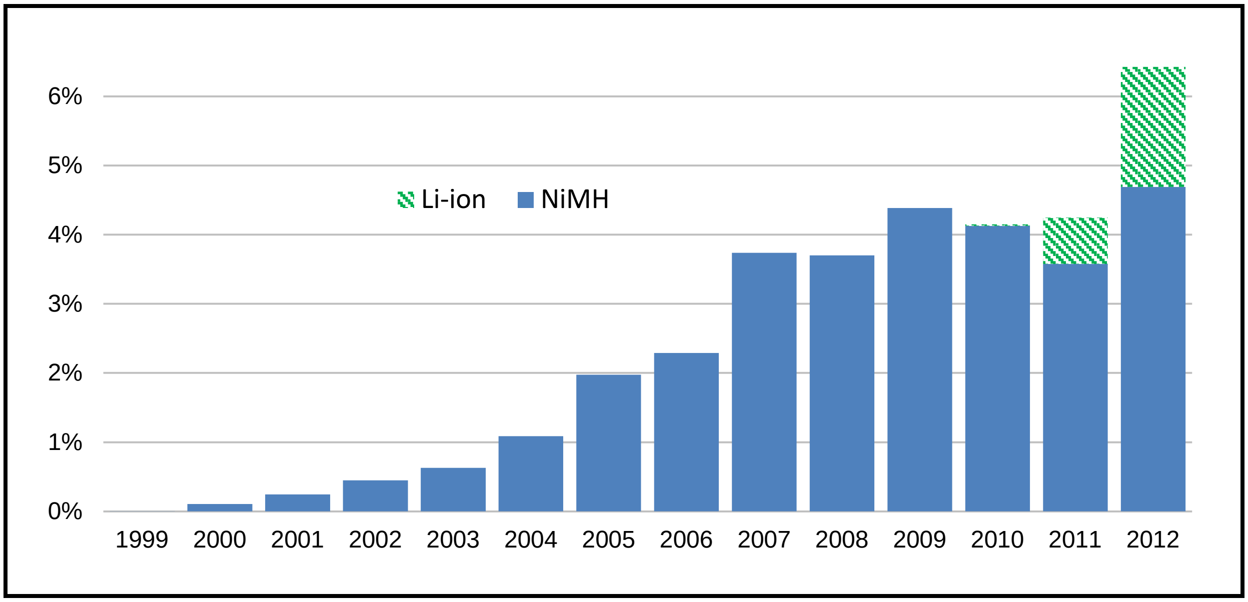
Source: This figure combines the EDV sales data from Appendix C with U.S. car data from Wards Auto (http://wardsauto.com/keydata/historical/UsaSa01summary).

Milestones in the commercial introduction of EDVs include the following:

- HEVs with NiMH batteries: Honda's Insight appeared on the U.S. market in 1999, followed by the Toyota Prius (2000) and Honda Civic Hybrid (2002). Hybrid versions of the Ford Escape and Mercury Mariner were the first hybrid light-duty trucks and appeared in 2004.
- HEVs with Li-ion batteries: Mercedes introduced Li-ion-powered cars to the United States in 2010 with the S400 luxury sedan.
- PHEVs: The Chevrolet Volt, powered by Li-ion batteries, entered the market in 2011 and was joined in the plug-in market in 2012 by Toyota's plug-in Prius PHEV.
- EVs: The Nissan Leaf (2011) and the Tesla Model S (2012) are early Li-ion EVs.

Figure 3-2 illustrates the annual market penetration of EDVs (omitting light-duty trucks) as a percentage of all U.S. car sales. Annual sales, by vehicle model and year, are presented in Tables C-1 through C-3 in Appendix C.

Figure 3-2. Percentage of Cars Sold in the United States Powered by NiMH or Li-ion Battery Technology, 1999–2012



Source: This figure combines the EDV sales data from Appendix C with U.S. car sales data from Wards Auto, http://wardsauto.com/keydata/historical/UsaSa01summary. Excludes light-duty trucks.

The overall annual market share of EDVs from 2009 to 2012 increased from over 4% to over 6%. This increase had much to do with the market availability and adoption of Li-ion batteries. Li-ion's share of the EDV market increased from 16% in 2011 to 27% in 2012 (Figure 3-1).

The overall market share of EDVs from 2009 to 2012 increased to over 6% of all new vehicle sales. This had much to do with the market availability and adoption of Li-ion batteries. Li-ion's share of the EDV market increased from 16% in 2011 to 27% in 2012.

The diffusion of NiMH and Li-ion technology through the market adoption of EDVs benefits both consumers and producers. Thus, using economics terminology, the diffusion of NiMH and Li-ion batteries generates consumer and producer surplus as well as broader-based social benefits in terms of avoided adverse health incidence associated with reduced vehicle emissions. These health benefits stem from the improved fuel efficiency of EDVs compared with conventional internal combustion vehicles (ICVs); less gasoline is needed to travel a given distance.

Fuel costs to the driver and the environmental and health costs to society are reduced when ICVs are displaced by EDVs. A portion of these benefits can be attributed to VTO's R&D investments to the extent (quantified in Sections 5 and 6) that experts deem these investments to have accelerated the availability and market diffusion of NiMH and Li-ion battery technologies in EDVs.

4 Methodology

This section provides an overview of the benefit-cost analysis framework and methodology used to quantify the social benefits of VTO's R&D investment in NiMH and Li-ion battery technology. The evaluation followed EERE guidelines for retrospective benefit-cost analyses (Ruegg & Jordan, 2011); a distillation of key points from these guidelines is presented in this section.

Note that as a result of this study's principally retrospective focus, the findings presented in Sections 5 through 9 understate the long-run social impact of VTO's R&D investments in NiMH and Li-ion battery technologies made before 2013. Impacts resulting from VTO energy storage investments made in 2013 and beyond were not considered. Impacts were also not considered for VTO-funded battery improvements embodied in EDVs sold in 2013 and beyond.

4.1 BENEFIT-COST ANALYSIS FRAMEWORK

This study identifies and documents four categories of impacts:

- energy and resource,[19]
- environmental,
- energy security, and
- knowledge.

Energy and resource benefits are related to the value of goods and services in the economy and include energy-related savings. Advancements in technology are one avenue through which economic benefits increase. Economic benefits accrue to society through the improved performance of existing goods

[19] Although energy is an economic resource, the term *energy and resource* is used in this evaluation given EERE's mission.

and services and/or through reductions in the cost of existing goods and services. Resource savings, such as energy savings, labor savings, capital savings, or material savings, are often significant sources of economic benefit. The largest source of economic benefits quantified in this study is fuel savings.

As a result of this study's principally retrospective focus, the findings presented in this report understate the long-run social impact of VTO's R&D investments in NiMH and Li-ion battery technologies.

Environmental benefits are principally changes in pollutant emissions associated with changes in the physical units of fossil-fuel energy consumed. Given the relationship between pollution and environmental health, another stream of economic benefits may accrue through a reduction in the incidence of adverse health events. These are termed environmental health benefits. Environmental health benefits may result from emissions changes related to changes in fossil fuel combustion.

Energy security benefits refer to the changes in risks to the national energy infrastructure, national energy independence, and exposure to exogenous (non-U.S.) volatility in fossil fuel trade.

Knowledge benefits are derived from the creation and dissemination of explicit knowledge as codified in patents, publications, relational networks, and tacit knowledge traceable to NiMH and Li-ion battery research.

Economic benefits for fuel savings and environmental health resulting from VTO's R&D investments in NiMH and Li-ion battery technologies were quantified in monetary terms in this evaluation. Energy security and knowledge benefits were described in quantitative and qualitative ways, but not in monetary terms per Ruegg and Jordan (2011).

4.2 CONCEPTUAL APPROACH TO BENEFIT-COST ANALYSIS

Griliches (1958) and Mansfield et al. (1977) pioneered the application of fundamental economic insight into the development of estimates of private and social rates of return to public and private investments in R&D.[20] Streams of investment outlays through time—the costs—generate streams of economic surplus through time—the benefits. Once identified

[20] A critical discussion of the Griliches and Mansfield et al. models is in Link and Scott (2010).

and measured, these streams of costs and benefits are used to calculate rates of return, benefit-to-cost ratios, and other performance measures.

Economic benefits were determined by the retrospective fuel savings associated with the actual diffusion and operation of EDVs compared with the counterfactual diffusion and operation of EDVs in the absence of VTO's R&D investments.

The Griliches/Mansfield model for calculating economic social rates of return compares the public investments through time—social investment costs—to measured private and public benefits. The evaluation question that can be answered from such an evaluation analysis is: *What is the social rate of return to the program's investments?*

This evaluation builds on the Griliches/Mansfield model in terms of comparing, in a systematic way, public benefits of VTO's R&D investments with the costs of those investments (see Link and Scott, 2011). Our analysis departs from the Griliches/Mansfield model in that we measure public benefits indirectly on the basis of a counterfactual experiment—what would the state of market adoption of EDVs have been in the absence of VTO's R&D investments—rather than directly in terms of an approximation consumer and producer surplus.

4.3 APPROACH TO ENERGY AND RESOURCE BENEFITS ESTIMATION

Interviewees were first asked to quantify changes in battery technology that resulted from VTO's R&D investments. Then they were asked to translate improvements to an increase in the commercial availability of and diffusion of EDVs throughout the United States.

Economic benefits were measured in terms of the fuel savings associated with the diffusion and operation of EDVs throughout the United States resulting from to VTO's R&D investments. The monetized value of counterfactually determined fuel savings is the principal economic benefit to society associated with VTO's R&D investments. Part of these fuel-savings benefits are captured by individuals in the form of consumer surplus, and part by firms in terms of producer surplus (i.e., the generally higher prices that consumers pay for EDVs compared with ICVs).

Interviewees (discussed in Section 5) were first asked to quantify changes in battery technology—battery life (years), energy density (Wh/kg), and cost ($/kWh)—associated with VTO's R&D investments. Then interviewees were asked to translate those technology improvements to an increase in the commercial availability of and diffusion of EDVs. Using extant information, the incremental increase in EDV availability and diffusion was converted into fuel savings.

Two important issues are related to this approach to estimating energy and resource benefits. The first relates to identifying the next best technology alternative, and the second relates to ensuring that impacts are the direct result of VTO's investments in NiMH and Li-ion battery technologies.

4.3.1 Estimation of Benefits Relative to the Next Best Technology Alternative

In this type of benefit-cost evaluation, the counterfactual situation is often defined in terms of the next best technology alternative. The question to consider is: In the absence of public funding of the new technology under study, how would the existing technology have developed on its own?

The next best technology alternative in this study is less developed NiMH and Li-ion battery technologies as determined by technical performance characteristics (see Table 2-1), assuming that the EDVs that the battery technologies were intended to power were commercially viable with inferior batteries.

The next best technology alternative are less developed NiMH and Li-ion battery technologies as determined by technical performance characteristics. We also consider whether the EDVs that the technologies were intended to power were even commercially viable, given the batteries' inferior technical performance characteristics.

Background research and preliminary discussions with industry experts revealed two important considerations for our specification of the counterfactual, discussed further in Section 5. The first consideration is that VTO's R&D investments accelerated and enhanced the development and vehicle-specific application of NiMH and Li-ion battery technologies, thus accelerating the adoption of the technologies as commercialized innovations embodied in EDVs. Yet, NiMH technology development in particular was not exclusive to the United States, and there was some probability that the technology would have diffused in the United States in the absence of VTO funding.

The second consideration is that diverse interviewees across the battery supply chain were more informed about the diffusion of NiMH and Li-ion batteries in EDVs than about how original equipment manufacturers (OEMs) would have redesigned their products in the face of inferior technical characteristics. Experts interviewed during our early background research phase indicated that those individuals who were identified to participate in the main data collection task would be able to assess the proportion of EDVs that would not exist in the absence of VTO's investments. But they would not be able to assess the extent to which EDVs would be less efficient given inferior battery technologies. If interviewees were able to do so, their response would be reflected in their assessment of EDV market adoption.

Thus, for this evaluation, we explored the diffusion of EDVs with NiMH and Li-ion batteries with and without VTO funding but did not quantify the extent to which those EDVs that do diffuse in the absence of VTO may be technically less efficient. This, of course, means that our economic performance measures are conservative.

4.3.2 Attribution of Benefits to VTO's Investments in NiMH and Li-ion Battery Technologies

VTO's specific role in supporting the adoption of EDVs with NiMH and Li-ion batteries was determined through detailed interviews with informed industry experts and VTO-funded companies and universities, as discussed at length in Section 5. All information collection methods were carried out in a manner such that the explicit data collected and the implicit insight gained were directly and specifically linked to quantifying and measuring social benefits with and without VTO's R&D investments in battery energy storage technologies.

4.4 APPROACH TO ENVIRONMENTAL BENEFITS ESTIMATION

Environmental benefits associated with VTO's R&D investments in NiMH and Li-ion battery technologies were quantified on the basis of fuel savings. Emissions reductions were quantified by applying emissions factors to fuel savings estimates. These emissions reductions were also inputted to the Co-Benefits Risk Assessment (COBRA) model, developed by the U.S. Environmental Protection Agency (EPA). The COBRA model provides estimates of health effect impacts and the economic value of avoided health care resulting from changes in the physical units of emitted pollutants. The COBRA model is discussed at length in Section 6.

4.5 APPROACH TO ENERGY SECURITY BENEFITS ESTIMATION

Energy security benefits are measured in terms of the reduction of our nation's dependency on imported crude oil. Fuel savings from increased fuel economy were converted to gallons of crude oil saved and compared with oil importation by the

United States over the time period of the analysis. Following EERE's evaluation guidelines (Ruegg & Jordan, 2011), energy security impacts were not considered quantitatively in calculating social economic returns in Sections 8 and 9.

4.6 APPROACH TO KNOWLEDGE BENEFITS ESTIMATION

Knowledge benefits were measured in terms of patent counts and comparable citation rates associated with VTO's R&D investments in NiMH and Li-ion technologies. Again, following EERE's guidelines (Ruegg & Jordan, 2011), knowledge benefits were not considered quantitatively in calculating social economic returns in Sections 8 and 9.

4.7 MEASURES OF SOCIAL ECONOMIC RETURN

Three performance measures of net social benefits were calculated:

- net present value (NPV),
- benefit-to-cost ratio (BCR), and
- internal rate of return (IRR).

NPV, according to Circular A-94 of the Office of Management and Budget (OMB) (OMB, 1992, p. 3), is a standard evaluation criterion for deciding whether a government program can be justified on economic principles—the discounted monetized value of expected net benefits (i.e., benefits minus costs). NPV is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. Discounting benefits and costs transforms gains and losses occurring in different time periods to a common unit of measurement. Generally, projects with positive NPV should be undertaken and those with negative NPV should not. Among those projects with positive NPVs, the larger the value of NPV the greater the net benefits to society.

BCR is the ratio of the present value of benefits to the present value of costs. A BCR greater than 1 indicates that the present value of quantified benefits outweighs the present value of calculated costs. The larger the value of a BCR, the greater the net benefits to society.

IRR is the discount rate that sets NPV equal to zero, or it is the discount rate that would result in a BCR equaling 1. The IRR's value can be compared with conventional rates of return for comparable or alternative investments. An IRR value greater than the return on an alternative investment (generally measured as equal to the discount rate) is interpreted to mean that the project was, in a comparative sense, socially valuable.

The specific formulae for these three measures are presented and discussed in Sections 8 and 9.

Fundamental to the calculation of NPV and a BCR is the discount rate used to reference all values to the initial time period in which investment costs began. Following OMB (1992) guidelines, a 7% real (i.e., adjusted for inflation) rate of discount was used. The use of a real discount rate means that all measured benefits and all investment costs are first converted into real, constant dollars to account for inflation, before they are discounted. According to OMB (1992, p. 8): "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent."

For comparative purposes only, and following the more recent suggestion in OMB Circular A-4 (OMB, 2003), a 3% real rate of discount was also used in the NPV and BCR calculations in Sections 8 and 9.[21]

[21] For federal economic evaluations, OMB issues directives on discounting and discount rates for different types of evaluations. Circular A-94 (OMB, 1992) directs the use of a 7% real discount rate for federal benefit-cost analysis. More recent guidance is provided by Circular A-4 (OMB, 2003), which pertains to benefit-cost analysis used as a tool for regulatory analysis. It notes that Circular A-94 stated that a real discount rate of 7% should be used in benefit-cost analysis as an estimate of the average before-tax rate of return to private capital in the U.S. economy. This rate is an approximation of the opportunity cost of capital. Circular A-4 further notes that OMB found in a subsequent analysis that the average rate of return to capital remained near 7%. It also points out that Circular A-94 recommends using other discount rates to show the sensitivity of the estimates to the discount rate assumption and notes that the average real rate of return on long-term government debt has averaged about 3%. Circular A-4 requires the use of both a 7% and a 3% real discount rate for a benefit-cost analysis conducted for regulatory purposes. When regulation primarily and directly affects private consumption (e.g., through higher consumer prices for goods and services), a lower discount rate is appropriate, and OMB suggests a 3% real rate of time preference. For the purpose of discounting constant dollar cash flows

In an economic evaluation such as this one in which all potential impacts were not quantified, and those that were quantified are truncated in time, it is important to emphasize that any performance measure will be conservative and thus will understate the true net benefits to society.[22]

in this study, both rates are used—a 7% and a 3% real discount rate—even though the purpose is not regulatory.

[22] It is also important to provide an accounting of other important effects, which may include nonmonetary quantitative and qualitative measures.

5 Energy and Resource Benefits

This section describes the estimation of fuel savings resulting from VTO's investment in NiMH and Li-ion battery technology R&D. It describes interview guide development, the interview sample of energy storage experts, counterfactual technology progression and EDV adoption, and avoided fuel consumption because of greater numbers of EDVs on the road resulting from technological progress funded by VTO.

For continuity of argument, performance measures for two time periods—1999 through 2012 and 1999 through 2022—were calculated separately, as described in this section and presented in Sections 8 and 9, respectively.

5.1 PRIMARY DATA COLLECTION PROTOCOL

During an early phase of this evaluation, general background information related to understanding the measurement of benefits was obtained through initial information interviews. Unstructured telephone interviews were held with several key individuals at USABC and at U.S. car companies who have a broad understanding of the supply chain for battery technology as well as the impact of technical improvements in battery technology on EDV market activity.

There was general agreement that VTO's R&D investments accelerated both the transition from conventional ICVs to EDVs and the diffusion of EDVs in the market.

Noteworthy from these informational interviews were two additional and important observations—important in the sense that they influenced both the construction of the interview guide from which economic benefits were ultimately identified and the interpretation of interview responses.

First, there was general agreement that VTO's R&D investments accelerated both the transition from conventional ICVs to EDVs and the diffusion of EDVs in the market. More specifically, those with whom we spoke acknowledged that there were indeed important technical improvements as a direct result of VTO's R&D investments. The consensus opinion was that these R&D

investments, and the subsequent technical improvements in NiMH and Li-ion battery technology, increased the rate of adoption of EDVs on the road by between 5 to 10 years.

Second, there was general agreement that the main impacts associated with VTO's R&D investments were associated with the increase in the rate of market adoption of EDVs. Those interviewed also noted that some vehicles may not have been commercially viable EDVs without VTO support, or those that would have been offered would have been less efficient. Information from these initial interviews is summarized in Table 5-1.

Information gleaned from experts participating in initial interviews informed the preparation of the interview guide used to collect impact data from DOE-funded companies and researchers. The guide was used as a pedagogical device to focus the telephone interviews and to ensure that the data collected represented the impacts directly resulting from VTO's R&D investments.

Prior to a telephone interview, each industry scientist who accepted the electronic invitation to participate in this study was sent electronically a copy of the interview guide. Along with the interview guide was information on the purpose and scope of this study and an emphasis on the fact that the interview guide was to "guide" the discussion about the impacts associated with VTO's R&D investments. Scientists at university and national laboratories were sent electronically the interview

Table 5-1. Consensus Opinions from Individuals Interviewed at USABC and at U.S. Car Companies

- VTO's R&D investments in energy storage technologies accelerated the transitional period from the use of lead acid battery technology to alternative battery technology and the resulting adoption of EDVs on the road by 5 to 10 years.
- Universities were not involved in NiMH battery research in the 1990s and afterwards; NiMH battery research was industry driven.
- Absent VTO's R&D investments, the U.S. automotive industry would today likely be importing all of its Li-ion batteries.
- There has been a significant lag in time between VTO's R&D investments and the realization of that technology as an innovation used in EDVs.
- The major economic impact of VTO's R&D investments is primarily realized through the increase in the market adoption of EDVs.

guide, and each was asked to complete it as a survey instrument and return it electronically; in rare cases were university or government laboratory scientists interviewed by telephone.

Questions 1 and 2 on the interview guide ask respondents to describe current and previous R&D projects related to NiMH and Li-ion technologies and how those projects had been affected by VTO's investments. Responses to these questions provided additional background information that complemented what was learned from the initial informational interviews summarized in Table 5-1. Questions 1 and 2 are important questions. Responses assured us that the individual with whom we were interviewing was not only familiar with VTO's R&D investments, but also knowledgeable about NiMH and Li-ion battery technology. In two instances we curtailed our interview because the scientists were deemed to be insufficiently qualified to offer an informed opinion about the impact of VTO's R&D investments.

The remaining questions on the interview guide ask respondents to consider a counterfactual situation in which VTO had not supported NiMH and Li-ion battery technologies through its R&D investments.

Question 3 asks how industry-wide battery research efforts and outcomes would have been different without VTO's funding support.

Question 4 asks how the advancement in the state-of-the-art battery technology over roughly the past 15 years would have been different without VTO support. Respondents were presented with schematics showing the advancement of NiMH and Li-ion battery technologies in three dimensions: battery life, gravimetric energy density, and cost. These schematics that were provided to the interviewees in the interview guide were derived from DOE sources, EERE merit review presentations,[23] and International Electronics Manufacturing Initiative (iNEMI) roadmaps.[24] Thus, each interviewee was provided with an informed description of the current state-of-the-art for NiMH and Li-ion battery technologies. Respondents

[23] See, for example, https://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_reports.html.

[24] See http://www.inemi.org/2013-roadmap.

were then asked to describe verbally the counterfactual situation without VTO support and to confirm their verbal descriptions using a graphical device in the interview guide.

Care was taken to emphasize to each interviewee that we realized that a number of factors influenced the current market share of EDVs and that the counterfactual aspect of Question 5 only considered the impact of VTO's support. Such factors included the global acceptance of EDVs, technical advancements by Japanese battery manufacturers, and U.S. regulations such as increased Corporate Average Fuel Economy (CAFE) standards.

Question 5 asks how the market adoption of NiMH and Li-ion battery technologies through the purchase of EDVs in the United States would have been different in the counterfactual situation of no VTO support. Interviewees were presented with factual information describing the current market share of EDVs in the United States from 1999 to 2011. Each was asked to describe the counterfactual situation of what the market adoption of EDVs would have been in the absence of VTO's support. Care was taken during this discussion to emphasize to each interviewee that we realized that a number of factors influence the current market share of EDVs and that the counterfactual aspect of Question 5 only considered the impact of VTO's support. Such factors included the global acceptance of EDVs, technical advancements by Japanese battery manufacturers, and other U.S. regulations such as increased Corporate Average Fuel Economy (CAFE) standards. Then, after a careful discussion of the counterfactual issue that we wanted to consider, each interviewee was asked to confirm his/her description using the schematics.

The market adoption over time is related to changes in both the supply and the demand of EDVs, and certainly separating supply effects from demand effects is important from an economic perspective and it is complicated. However, for the purpose of this study we are only interested in the resulting increase in EDVs on the road.

Embedded in the discussion of Question 5 is the issue of attribution, as discussed above. To ensure that each interviewee was indeed offering an assessment about the counterfactual market adoption of EDVs in the absence of VTO's R&D investments, clarification was asked in Question 7. To transition to Question 7, we first asked in Question 6 about the share of the EDV market in the United States with Li-ion battery technology in the absence of VTO's support.

Question 7 was intended to confirm that each interviewee did indeed understand the nature of the counterfactual inquiry because his/her responses to Question 5 would be the basis for the quantification of benefits. Question 7 asked the respondent whether the reported impacts were entirely due to VTO R&D

investments. Nearly 90% of those interviewed indicated that they fully understood the nature of our counterfactual inquiry. Only five respondents paused and told us that part of their graphical response to Question 5 did include other economic impacts such as the global acceptance of EDVs and technical advancements by Japanese battery manufacturers.

5.2 SAMPLE OF INTERVIEWEES AND RESPONDENTS

Two overlapping sources were used to identify a sampling population: information from VTO personnel on companies that VTO had funded and VTO annual reports. The sampling population consisted of three sources of experts:

- scientists in companies funded by VTO for either NiMH or Li-ion battery research,
- university scientists funded by VTO for either NiMH or Li-ion battery research, and
- national laboratory scientists funded by VTO for either NiMH or Li-ion battery research.

The following discussion illustrates the representativeness—in terms of receipt of DOE R&D and in terms of stages in the battery value chain—of the sample of those who were interviewed and thus from whom relevant evaluation data were obtained.

The funded organizations (companies, universities, and national laboratories) considered for the sampling population totaled 148. Column (2) of Table 5-2 shows the number of funded organizations, by category, as reported by VTO in its annual reports.

As shown in column (3) of Table 5-2, contact information was obtained for scientists at 95 of the 148 organizations, or 64% of the sampling population.[25] RTI attempted a full census of funded organizations; however, many organizations were no longer operating or had merged with or been acquired by other firms.

[25] Contact information was obtained for at least one scientist at all of the university and national laboratories but only for at least one scientist at 49% of the funded companies.

Table 5-2. Participants in the Data Collection Process, by Stakeholder Category

(1) Category of Organization	(2) Funded by DOE/USABC Since 1992	(3) With Contact Information (percentage of funded organizations)	(4) Organizations Interviewed/ Surveyed (percentage of contacted organizations)	(5) Number of Individuals Participating
Companies	104	51 (49%)[a]	25 (49%)	25
Universities	28	28 (100%)	5 (18%)	6
National laboratories	16	16 (100%)	10 (63%)	23
Total	148	95 (64%)	40 (42%)	54

[a] In actuality, the number of companies with contact information would be significantly higher if adjustments were made for merger and acquisition activity. Note: Table D-1 in Appendix D lists all companies, universities, and national laboratories that participated in the survey.

Fifty-four participants from 40 of the 95 organizations for which there was contact information agreed to participate in the study directly by telephone or indirectly by a personalized electronic survey. These 54 participants represent an average organization coverage ratio of 42%.

No information is available as to why some who were invited to participate declined to do so. Viewing company responses (n=25) in isolation from the university and national laboratory responses (n=29) was considered. However, as described in Appendix E, this approach was rejected because there is no evidence that the responses between the two groups are statistically different.

54 experts from 40 organizations agreed to participate in this evaluation.

The organizational group most heavily represented in the sample was funded companies (n=25). Scientists from these companies were either current or former R&D managers; thus, each was able to provide through his/her responses a broad perspective about the EDV market.

Collectively, these 25 companies were the recipients of

- 98% of VTO's R&D investments in NiMH battery technology and
- 76% of VTO's R&D investments in Li-ion battery technology.

The R&D funding to these companies came through USABC contracts between 1995 and 2010, based on USABC contract funding summaries provided by DOE (see Table 5-3).

Table 5-3. Distribution of Company Participants, by Battery Technology Area

(1) Battery Technology Area	(2) DOE R&D Investment in USABC Contracts, 1995–2010 ($millions)	(3) R&D Investment Amount Represented in Our Sample ($millions)	(4) Percentage of USABC Contract R&D Investment Represented in Our Sample
NiMH	29.8	29.2	98%
Li-ion (including lithium polymer)	157.6	119.0	76%

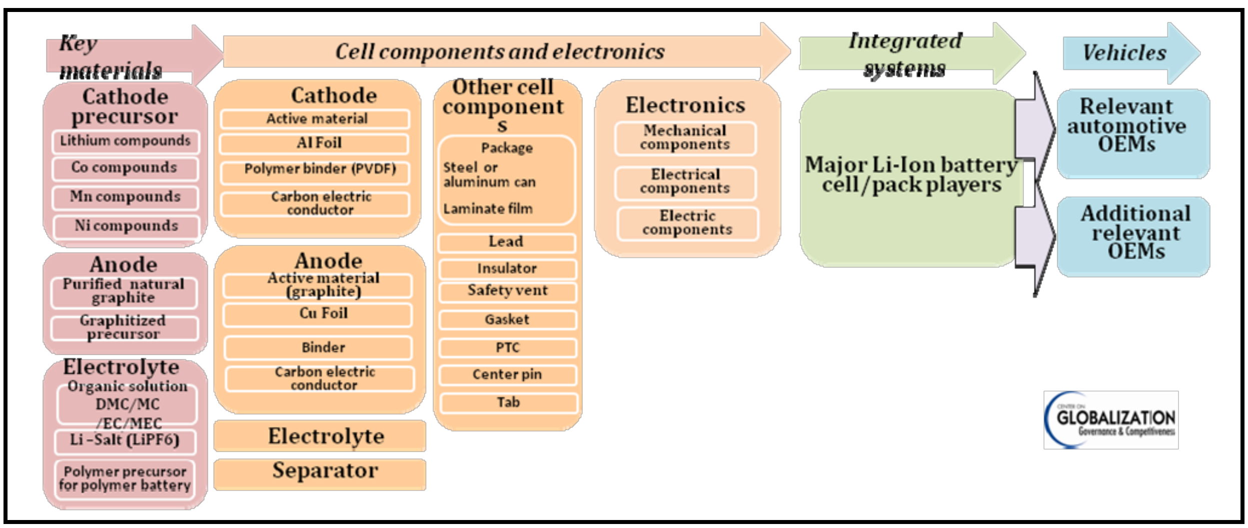
Note: n =25. Source: USABC Contract Summary 1995–2010, provided by DOE.

DOE provided R&D funding to 41 companies in five major segments along the Li-ion value chain as characterized by Figure 5-1. Among the 25 company respondents are 22 of those 41 companies (see column [2] in Table 5-4):

- 3 of 7 key materials manufacturers
- 6 of 13 cell components and electronics manufacturers
- 7 of 9 integrated systems manufacturers
- 2 of 2 OEMs
- 4 of 10 U.S. venture capital startups

Table D-1 in Appendix D lists all companies, universities, and national laboratories that participated in primary data collection.

Figure 5-1. Value Chain of Li-ion Batteries for Vehicles



Source: Lowe et al. (2010, p. 33). Reproduced with permission of the Center on Globalization, Governance & Competitiveness at Duke University.

Table 5-4. Distribution of Evaluation Participants along the Li-ion Battery Value Chain

(1) Value Chain Segments	(2) Companies Receiving VTO Funding for Li-ion Research	(3) VTO-Funded Companies Interviewed	(4) Coverage Ratio by Value Chain Location
Key materials	7	3	43%
Cell components and electronics	13	6	46%
Integrated systems	9	7	78%
Vehicle OEMs	2	2	100%
U.S. venture capital startups	10	4	40%
Total	41	22	54%

Note: OEM refers to original equipment manufacturers. Table D-1 in Appendix D lists all companies, universities, and national laboratories that participated in the survey. Value chain segments based on Lowe et al. (2010, p. 34).

5.3 COUNTERFACTUAL BATTERY LIFE, ENERGY DENSITY, AND COST IMPROVEMENT WITHOUT VTO'S R&D INVESTMENTS

Interviewees were asked how industry-wide battery research efforts and outcomes would have been different in the absence of VTO's support. One firm noted, and the theme of this response is representative of many of the respondents, that "[w]ithout DOE, there would be essentially no U.S. industry. Technology would still have been developed abroad in, e.g., Japan and Korea, and EDVs would still have made their way into the U.S. market, but it would have taken longer."

The mean response was that VTO investment accelerated industry-wide R&D investments by just over 6 years, with a standard deviation (std. dev.) of less than 1 year (see Table 5-5).[26]

[26] This interview finding complements the information learned through the initial informational interviews. VTO's investment increased the transition from lead acid battery technology to alternative battery technologies and the resulting adoption of EDVs on the road by 5 to 10 years (Table 5-1).

Table 5-5. Battery Life, Energy Density, Cost, and Li-ion EDV Sales Improvements from VTO's R&D Investments

Metric	(1) Mean	(2) Std. Dev.	(3) n
Number of years by which industry-wide R&D was accelerated by VTO	6.1 years	0.8	15
Percentage of progress from 1998 to 2012 funded by VTO			
Battery life	35%	3	38
Energy density—NiMH	33%	5	37
Cost—NiMH	30%	4	37
Energy density—Li-ion	33%	12	12
Cost—Li-ion	33%	8	12
Percentage of Li-ion vehicle sales resulting from technological improvements funded by VTO	64%	7	21

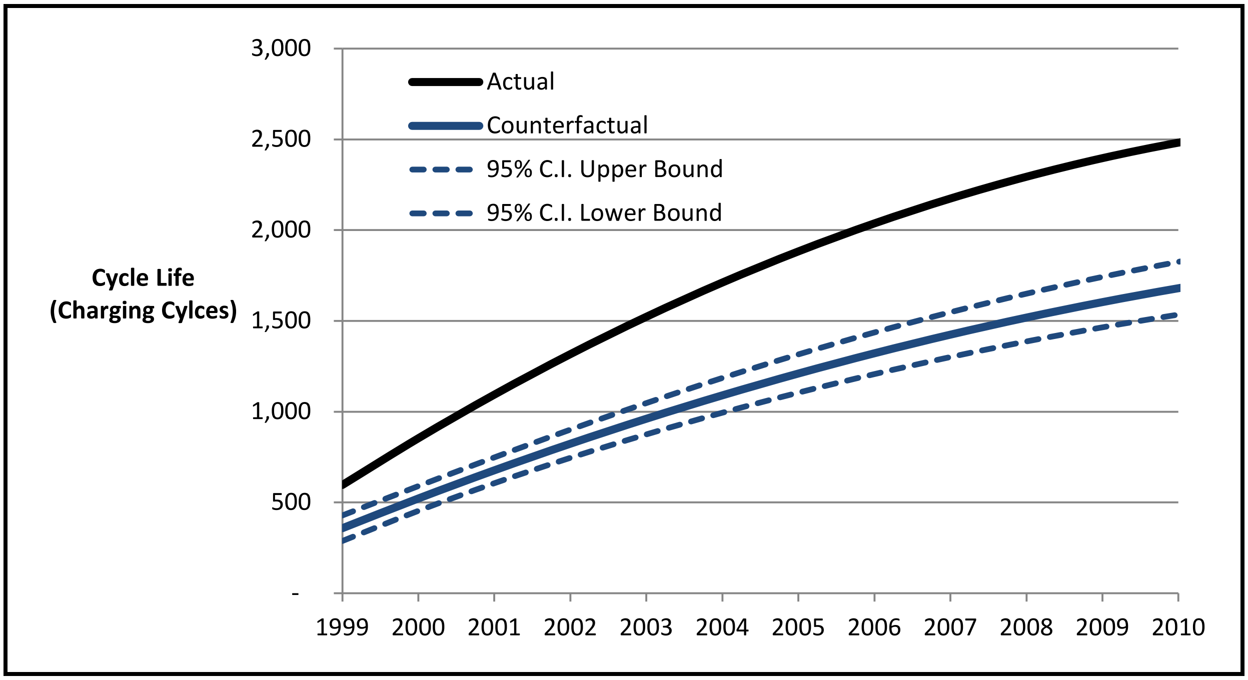
Note: The conventional estimate of the standard deviation of the sample mean, calculated by dividing the standard deviation of the sample of n answers by the square root of n, is reported.

Interviewees collectively stated that VTO accelerated industry-wide R&D investments by just over 6 years, with a standard deviation of less than 1 year.

Interviewees described advancement in the state-of-the-art characteristics of NiMH and Li-ion batteries since 1998 from VTO support. From the responses to these questions it appears to be the mean opinion that battery life has improved by 35%, energy density for both NiMH and Li-ion batteries has improved by 33%, and the cost of NiMH batteries has decreased by 30% and that of Li-ion batteries by 33%—see column (1). Figures 5-2, 5-3, and 5-4 illustrate the interviewees' responses for Li-ion battery technology (see counterfactual curves in these figures).

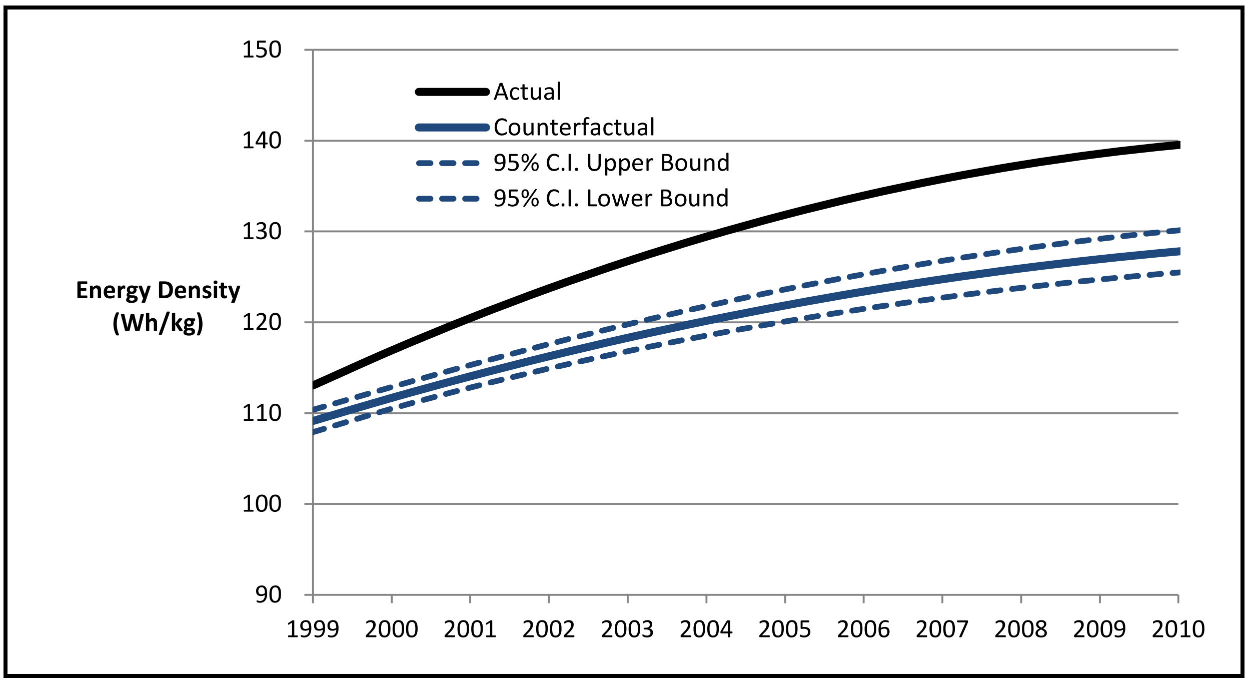
Lastly, the market for Li-ion batteries would be 36% (1.0 – 0.64) of what it is in the absence of VTO's R&D investments in that technology (Table 5-5). One automobile company executive noted that "[i]t is possible that without the [VTO's] support for battery technology development, there might presently be no Li-ion technology in the EDV market. The influence on U.S. automakers is evident with all offering EDVs exclusively with Li-ion technology."

Figure 5-2. Counterfactual Battery Life Improvement without VTO's R&D Investments



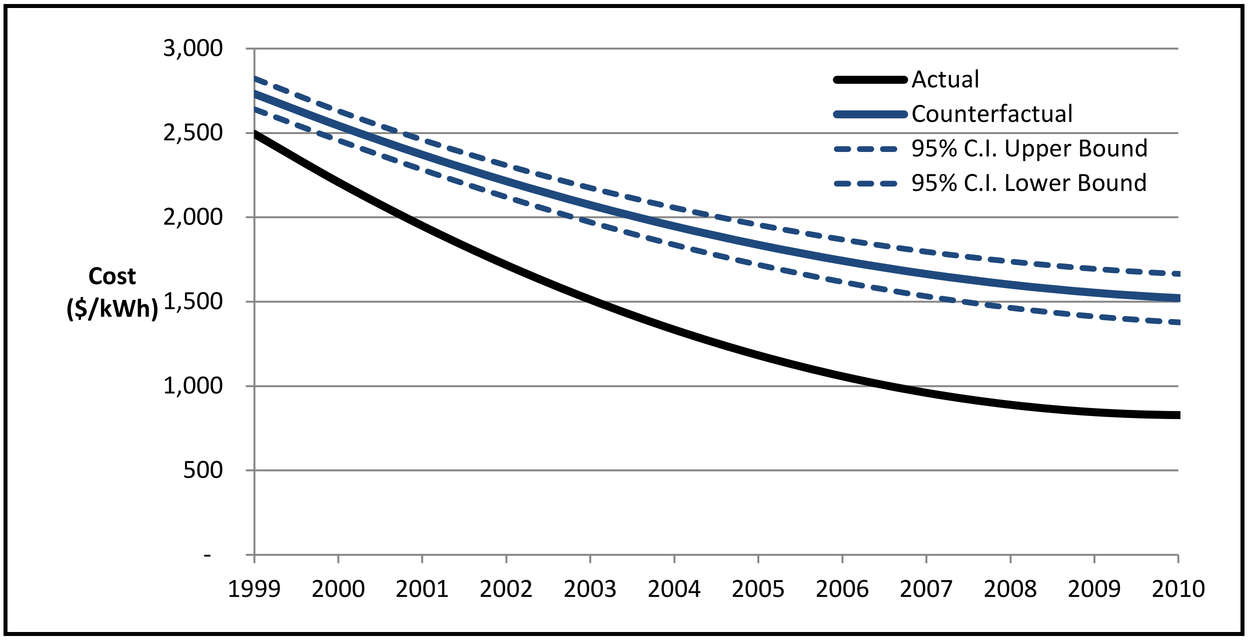
Note: C.I. denotes confidence interval.

Figure 5-3. Counterfactual Energy Density Improvement without VTO's R&D Investments



Note: C.I. denotes confidence interval.

Figure 5-4. Counterfactual Cost Improvement without VTO's R&D Investments



Note: C.I. denotes confidence interval.

One interviewee noted that "[i]t is possible that without the VTP's support for battery technology development, there might presently be no Li-ion technology in the EDV market. The influence on U.S. automakers is evident with all offering EDVs exclusively with Li-ion technology."

As of this evaluation's timing (2012), Li-ion EDVs were in their earliest stages of adoption. It was assumed that, for 2011 and 2012, a consumer seeking to adopt an EDV would adopt a NiMH-powered vehicle as a substitute for a Li-ion–powered one (e.g., the Ford Fusion or Toyota Camry in lieu of the Hyundai Sonata or Kia Optima). However, this assumption may not hold beyond this evaluation because the performance characteristics of Li-ion–powered EDVs and new models or types of EDVs may enter the marketplace beginning in 2013.

For example, vehicles such as the Tesla Model S and Nissan Leaf, which respectively achieved sales of 2,400 and 9,800 units in 2012, may be adopted in increasing numbers in future years, and these do not at present have near-perfect NiMH-powered substitutes. Interviewees believe the influence of VTO on Li-ion battery technology to be greater than on NiMH technology. As more Li-ion EDVs are adopted, the returns to VTO's investment will increase, warranting revisiting the calculations in this evaluation.

5.4 COUNTERFACTUAL EDV ADOPTION WITHOUT VTO'S R&D INVESTMENTS

Interviewees were asked to consider the market adoption of EDVs in the United States since 1999 (see Figure 3-2 in Section 3) under a counterfactual situation of no VTO R&D investments for either NiMH or Li-ion battery technology development. Interviewees described their assessment of the counterfactual and confirmed their responses using the interview guide's schematics.[27] Thus, it was possible to estimate, by year, the incremental number of EDVs on the road resulting from progress funded through VTO's R&D investments.

The values in Table 5-6 summarize responses. These values were calculated using the four-step approach described below:

Step 1:
Each respondent was presented with a schematic of an adoption curve based on Figure 3-2. It is represented here as Figure 5-5.

The shape of the adoption pattern in Figure 5-5 can be mathematically expressed as a sigmoidal curve of the form:

$$P_t = M \Big/ \left\{ 1 + e^{\left(\frac{t^{mid} - t}{a}\right)} \right\} \quad (5.1)$$

where e is the base to the natural logarithms, M is the maximum attained by the sigmoidal curve, t is analytic time (in our case 1999 corresponds to $t = 0$), t^{mid} is the number of years taken by the curve to climb half of the way to M, and a is an index of how gradually the sigmoidal curve rises.

The units of M were chosen to be the percentage market share of EDVs (rather than the approximate number of EDVs sold), so P_t is likewise the percentage market share of EDVs at time t.

Step 2:
Each respondent's (respondent *i*'s) description and opinion were characterized in terms of the values M_i, t_i^{mid}, and a_i.

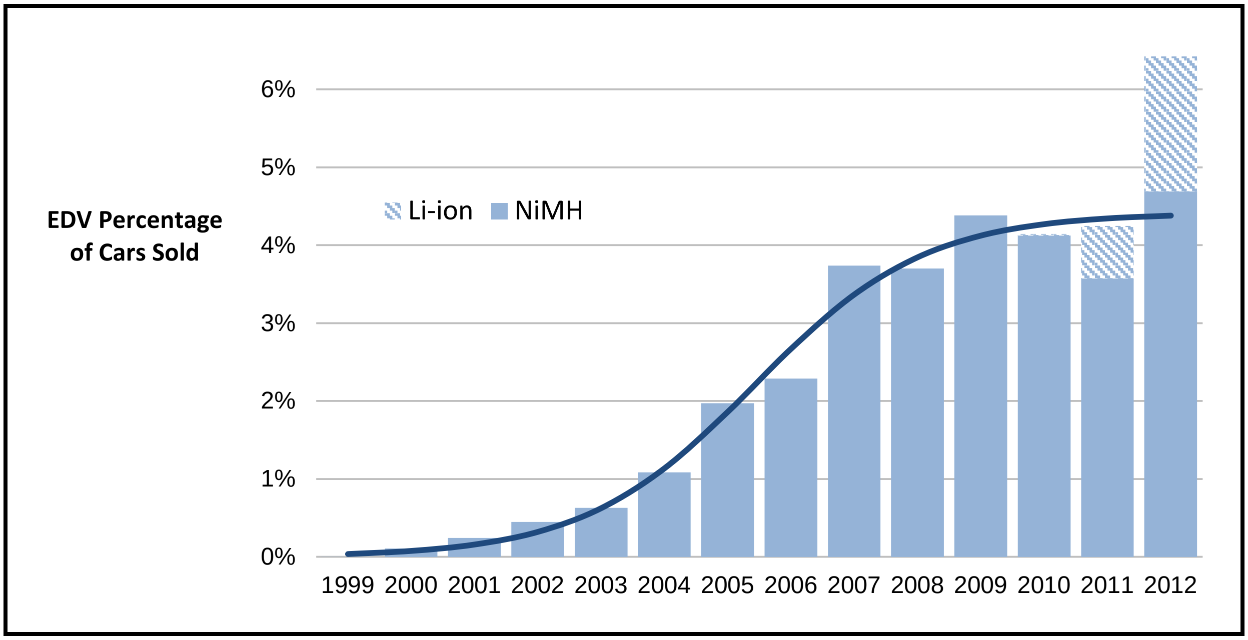
[27] None of those interviewed expressed any hesitance to respond to this data collection process, and the respondents were very thoughtful and conservative in the way that they discussed the impact of VTO's R&D investments.

Table 5-6. Percentage of Market Adoption of EDVs Resulting from VTO R&D Investments

Year	(1) Mean n=44	(2) Std. Dev.	Year	(1) cont. Mean n=44	(2) cont. Std. Dev.
1999	40	6	2006	50	4
2000	44	5	2007	47	4
2001	47	5	2008	44	4
2002	49	4	2009	41	4
2003	51	4	2010	38	4
2004	52	4	2011	36	4
2005	51	4	2012	34	4

Note: The conventional estimate of the standard deviation of the sample mean, calculated by dividing the standard deviation of the sample of n answers by the square root of n, is reported.

Figure 5-5. Market Adoption of EDVs in the United States Since 1999—Percentage of Cars Sold in the United States Powered by NiMH or Li-ion Battery Technology



Note: This is a reproduction of Figure 3-2 with the sigmoidal curve imposed. Figure is stylized based on total EDV sales through 2011.

Regarding attribution, as evidenced by a respondent's answer to Question 7, interviewees understood that Question 5 was intended to elicit their opinion about the adoption of NiMH and Li-ion technology technologies in the absence of VTO investments. Question 7 reiterated that fact to ensure that the difference between the actual and counterfactual adoption curves was due entirely to VTO's R&D investments. When an interviewee responded to Question 7 with a value less than

100%—and that happened in 5 of 44 interviews—that individual's response to Question 5 was adjusted or weighted to ensure that the values in Table 5-6 are entirely, in the opinion of the interviewee, the incremental impact of VTO's R&D investments.

Five of the 44 interviewees answered Question 7—*For clarification, are the differences that you have described between the actual and counterfactual scenarios due entirely to VTO's financial support of NiMH and Li-ion technologies?*—with a value of less than 100%. Their coded responses were recorded as weighted averages: $w_i M_i + (1 - w_i) M_0$, where w_i is the respondent's answer to Question 7 (as a decimal between 0 and 1), M_i is the parameter of the counterfactual curve, and M_0 is the parameter of the original curve shown to the respondent. The same adjustment was performed on t_i^{mid} and a_i.Emphasis on attribution to VTO's R&D investments during the discussion about Question 5, and again about Question 7, controls for several factors that are exogenous to VTO's R&D investments in battery technology. Those factors included, for example, global acceptance of EDVs, technical advancements by Japanese battery manufacturers, and other U.S. regulations (e.g., increased CAFE standards).

Step 3:
Based on each respondent's response to Question 5 and his/her response to Question 7, the parameterized values for M_i, t_i^{mid}, and a_i were translated into values for the years 1999 through 2012 (P_0^i, P_1^i, ..., P_{13}^i) and compared with the values associated with the adoption curve originally shown in Question 5. From this comparison, the percentage of EDV sales resulting from VTO support in each year (A_t^i is the percentage of EDV sales at time *t*, based on respondent *i*'s answer) is as shown in equation (5.2):

$$A_t^i = 100\left(1 - \frac{P_t^i}{P_t}\right) \quad (5.2)$$

Step 4:
For each year *t*, the percentage of market adoption of EDVs was averaged across the 44 (of 54) respondents who provided estimates during Question 5. See equation (5.3):

$$\overline{A_t} = \sum_{i=1}^{n} A_t^i / n \quad (5.3)$$

This average from equation (5.3) is reported for each year in Table 5-6. Figure 5-6 shows the actual and average counterfactual adoption curve, with a 95% confidence interval bounding the counterfactual adoption curve.

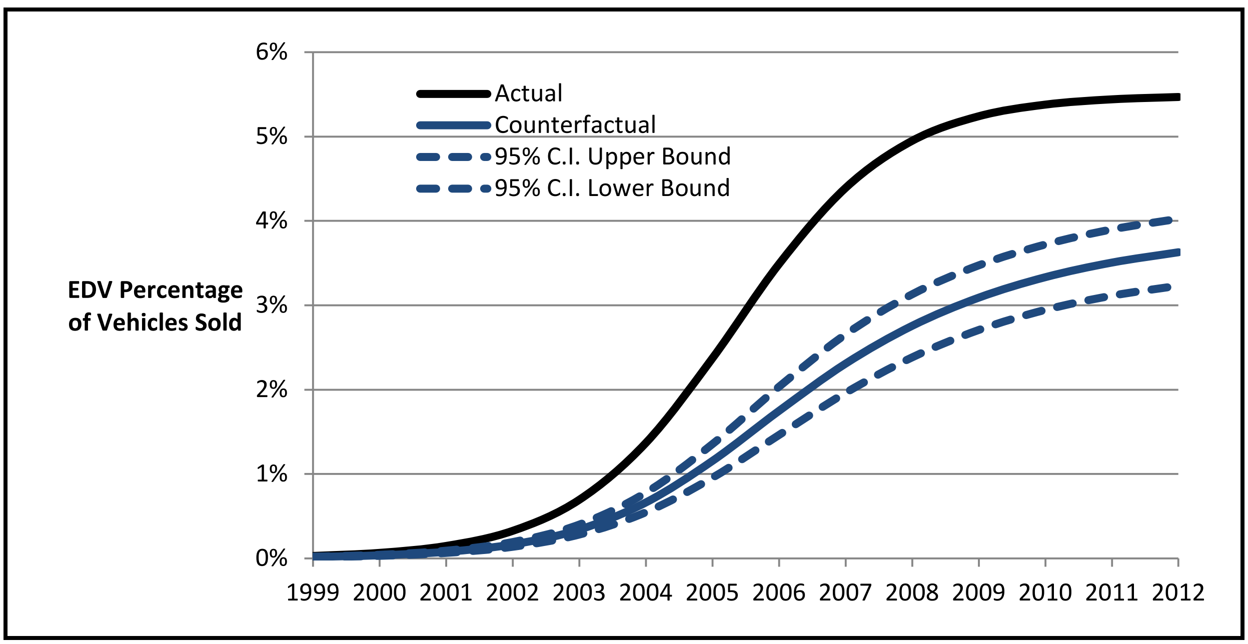
The mean values in column (1) of Table 5-6 are used to determine fuel savings associated with the economic impact of VTO's R&D investments on the market adoption of EDVs, as discussed below.

Figure 5-6 is a graphical summary of the interview-based data that underlie this evaluation study. This visual emphasizes, perhaps more than the foundational data in Table 5-6, the fact that informed scientists have differing opinions about the market impact of VTO's R&D investments.

5.5 FUEL SAVINGS FROM VTO'S R&D INVESTMENTS

Fuel savings from the accelerated adoption and operation of EDVs were the principal economic benefits calculated in this study. Fuel savings were measured using a three-step approach, as described below.

Figure 5-6. Counterfactual Market Adoption of EDVs in the United States without VTO's R&D Investments



Note: Figure is stylized based on total EDV sales through 2011. C.I. denotes confidence interval.

In essence, experts noted that there was some probability that EDVs would have been available in the absence of VTO's investments, but these EDVs would have been less efficient.

Step 1:
The market adoption of HEV, PHEV, and EVs resulting from R&D investments was calculated using interview responses. These values are in columns (5), (6), and (7) of Table 5-7, respectively.

In essence, experts noted that there was some probability that EDVs would have been available in the absence of VTO's investment, but these EDVs would have been less efficient due to less efficient battery technology. Recall from Section 4 that benefits are being conservatively estimated by only quantifying those EDVs that would not be on the road. (We are unable to quantify how relatively inefficient those that would be on the road would be because we do not know how OEMs would have redesigned the vehicle envelopes in the face of comparatively inferior battery performance.)

Step 2:
The number of miles driven for additional HEVs, PHEVs, and EVs on the road was calculated for different years using data on the average number of miles driven by vehicles of differing ages, as shown in Table 5-8. These data also established an assumption in our model that a vehicle remains on the road for 11 years and then is scrapped.[28]

Based on the assumption of a vehicle being scrapped after it has been 11 years on the road (i.e., one year after it has turned 10 years of age), Table 5-9 was constructed using the incremental increase in HEV sales in column (5) of Table 5-7. Note in Table 5-9 that the seven new HEVs purchased in 1999 continue to be on the road through 2009. The same process is repeated for PHEVs (Table 5-10) and EVs (Table 5-11).

[28] Additional support for this assumption comes from U.S. EPA Tier 2 requirements "Current data indicate that passenger cars are driven approximately 120,000 miles in their first ten years of life. Trucks are driven further. Current regulatory useful lives are 10 years/100,000 miles for light-duty vehicles and light-duty trucks and 11 years/120,000 miles for heavy light-duty trucks" (U.S. EPA, 2000, p. 6789).

Table 5-7. Incremental Market Adoption of HEVs, PHEVs, and EVs in the United States from VTO's R&D Investments

Year	(1) HEV Sales	(2) PHEV Sales	(3) EV Sales	(4) Percentage of Sales due to VTO-Sponsored R&D (rounded)	(5) HEV Sales due to VTO-Sponsored R&D (rounded)	(6) PHEV Sales due to VTO-Sponsored R&D (rounded)	(7) EV Sales due to VTO-Sponsored R&D (rounded)
1999	17			40	7		
2000	9,350			44	4,097		
2001	20,282			47	9,519		
2002	36,042			49	17,748		
2003	47,566			51	24,161		
2004	84,233			52	43,396		
2005	205,876			51	105,505		
2006	251,864			50	125,536		
2007	351,071			47	166,371		
2008	315,763			44	139,782		
2009	290,273			41	118,982		
2010	274,648			38	104,338		
2011	269,210	7,671	10,150	36	95,621	2,725	3,605
2012	434,498	38,585	14,587	34	146,021	12,967	4,902

Note: See Appendix C for sales data by vehicle model. Actual sales of each EDV type were multiplied by this average percentage to obtain the incremental sales values in columns (5) through (7) of Table 5-7 resulting from battery technical performance improvements funded by VTO.

Table 5-8. Average Miles Driven, by Vehicle Age

(1) Vehicle Age	(2) Average Annual Miles	(1) cont. Vehicle Age	(2) cont. Average Annual Miles
Under 1	14,350	6	11,950
1	14,450	7	11,750
2	13,950	8	11,200
3	12,900	9	11,050
4	12,550	10	8,350
5	12,400		

Note: The average annual miles driven, by vehicle age, is the average of 2001 and 2009 self-reported miles driven.

Source: DOE (2012, Table 8.10).

Table 5-9. Additional HEVs on the Road, by Year and Vehicle Age

	Years										
Year	**<1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1999	7										
2000	4,097	7									
2001	9,519	4,097	7								
2002	17,748	9,519	4,097	7							
2003	24,161	17,748	9,519	4,097	7						
2004	43,396	24,161	17,748	9,519	4,097	7					
2005	105,505	43,396	24,161	17,748	9,519	4,097	7				
2006	125,536	105,505	43,396	24,161	17,748	9,519	4,097	7			
2007	166,371	125,536	105,505	43,396	24,161	17,748	9,519	4,097	7		
2008	139,782	166,371	125,536	105,505	43,396	24,161	17,748	9,519	4,097	7	
2009	118,982	139,782	166,371	125,536	105,505	43,396	24,161	17,748	9,519	4,097	7
2010	104,338	118,982	139,782	166,371	125,536	105,505	43,396	24,161	17,748	9,519	4,097
2011	95,621	104,338	118,982	139,782	166,371	125,536	105,505	43,396	24,161	17,748	9,519
2012	146,021	95,621	104,338	118,982	139,782	166,371	125,536	105,505	43,396	24,161	17,748
2013		146,021	95,621	104,338	118,982	139,782	166,371	125,536	105,505	43,396	24,161
2014			146,021	95,621	104,338	118,982	139,782	166,371	125,536	105,505	43,396
2015				146,021	95,621	104,338	118,982	139,782	166,371	125,536	105,505
2016					146,021	95,621	104,338	118,982	139,782	166,371	125,536
2017						146,021	95,621	104,338	118,982	139,782	166,371
2018							146,021	95,621	104,338	118,982	139,782
2019								146,021	95,621	104,338	118,982
2020									146,021	95,621	104,338
2021										146,021	95,621
2022											146,021

Note: The values in this table are cumulative values from Table 5-7 in column (5). The values are based on the assumption that a vehicle is on the road for 11 years and is then scrapped.

As an illustrative example, consider the year 1999 when there are seven additional HEVs on the road in Table 5-9, all less than a year old. The seven vehicles are actually rounded from the following: Of the 17 vehicles sold in 1999 (column [1] of Table 5-7), 39.75% (40% or 0.40 in column [3] of Table 5-7) were because of the improved technical performance funded by VTO. Thus, 17 x 0.3975 = 6.7575 vehicles, rounded to seven vehicles in column (4) of Table 5-7. Although tables present rounded values, the calculations underlying them permitted fractional values.

Table 5-10. Additional PHEVs on the Road, by Year and Vehicle Age

	Years										
Year	**<1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2011	2,725										
2012	12,967	2,725									
2013		12,967	2,725								
2014			12,967	2,725							
2015				12,967	2,725						
2016					12,967	2,725					
2017						12,967	2,725				
2018							12,967	2,725			
2019								12,967	2,725		
2020									12,967	2,725	
2021										12,967	2,725
2022											12,967

Note: The values in this table are cumulative values from Table 5-7 in column (6). The values are based on the assumption that a vehicle remains on the road for 11 years and is then scrapped.

Table 5-11. Additional EVs on the Road, by Year and Vehicle Age

	Years										
Year	**<1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2011	3,605										
2012	4,902	3,605									
2013		4,902	3,605								
2014			4,902	3,605							
2015				4,902	3,605						
2016					4,902	3,605					
2017						4,902	3,605				
2018							4,902	3,605			
2019								4,902	3,605		
2020									4,902	3,605	
2021										4,902	3,605
2022											4,902

Note: The values in this table are cumulative values from Table 5-7 in column (7). The values are based on the assumption that a vehicle remains on the road for 11 years and is then scrapped.

Step 3:

Table 5-12 presents the calculated fuel savings for U.S. EDVs purchased from 1999 through 2012. Column (1) reports the sum of all columns for the given year from Table 5-9. Similarly, columns (2) and (3) report the sum of all columns for the given year from Tables 5-10 and 5-11, respectively.

Table 5-12. Fuel Savings of VTO R&D Investments for EDVs Sold between 1999 and 2012

	Rounded			Rounded, Thousands			Rounded, Thousands of Gallons	Rounded, thousands $2012
Year	(1) Additional HEVs on Road	(2) Additional PHEVs on Road	(3) Additional EVs on Road	(4) HEV Miles Driven	(5) PHEV Miles Driven	(6) EV Miles Driven	(7) Fuel Savings	(8) Fuel Cost Savings
1999	7			97			1	2
2000	4,104			58,895			814	1,611
2001	13,623			195,901			2,707	5,027
2002	31,372			449,485			6,211	10,773
2003	55,533			788,913			10,901	21,419
2004	98,929			1,393,754			19,258	43,500
2005	204,434			2,877,430			39,759	106,175
2006	329,970			4,632,866			64,015	187,326
2007	496,341			6,918,298			95,594	295,234
2008	636,123			8,736,302			120,714	423,230
2009	755,105			10,178,950			140,648	356,448
2010	859,437			11,337,092			156,651	461,639
2011	950,961	2,725	3,605	12,304,344	39,099	51,735	172,295	627,142
2012	1,087,462	15,692	8,507	13,925,831	225,450	122,442	200,216	736,723
2013	1,069,714	15,692	8,507	13,342,510	225,385	121,129	192,115	706,913
2014	1,045,552	15,692	8,507	12,614,769	216,040	114,893	181,701	668,594
2015	1,002,156	15,692	8,507	11,573,278	201,471	108,484	166,852	613,955
2016	896,651	15,692	8,507	10,115,326	196,524	106,227	146,549	539,246
2017	771,115	15,692	8,507	8,445,693	193,353	103,869	123,349	453,881
2018	604,744	15,692	8,507	6,519,018	186,972	100,942	96,523	355,171
2019	464,962	15,692	8,507	4,933,139	182,880	97,979	74,446	273,935
2020	345,980	15,692	8,507	3,563,269	175,340	94,742	55,283	203,423
2021	241,642	15,692	8,507	2,411,963	166,038	84,273	38,889	143,097
2022	146,021	12,967	4,902	1,219,271	108,276	40,933	20,048	73,768
1999–2012				73,798,158	264,549	174,176	1,029,784	3,276,249
1999–2022				148,958,220	2,116,827	1,147,649	2,125,539	7,308,232

Note: Columns (1), (2), and (3) are from Table 5-9. Columns (4), (5), and (6) are the products of EDVs by category and miles driven data from Table 5-8. Column (7) is the sum of the products of miles driven and fuel savings per mile data from Table 5-13. Column (8) is the product of fuel savings and gasoline price data from Table 5-14.

Column (4) reports the sum of miles driven by the number of vehicles in column (1). The sum of miles driven for a given year in Column (4) is obtained by multiplying the number of vehicles of each age (from Table 5-9) by the average annual number of miles driven by vehicles of that age (from Table 5-8) and summing all vehicle ages for the given year. The sums of miles in columns (5) and (6) are obtained in the same way from the numbers of vehicles in Tables 5-10 and 5-11.

For example, 97,000 miles for year 1999 in column (4) of Table 5-12 is the product of 6.7575 HEVs (rounded to 7 in Table 5-9) and 14,350 miles per year (from Table 5-8).

Column (7) in Table 5-12 represents the fuel savings by year based on the per-mile fuel savings in Table 5-13. For example, for 1999, 13.8 gallons of gasoline were saved for each thousand: 13.8 x 97 = 1,339 gallons of gasoline saved (rounded to 1 in thousands of gallons of gasoline saved).

Column (8) in Table 5-12 is the value of the fuel savings in column (7). This value is based on the average inflation-adjusted price of gasoline, by year, shown in Table 5-14. For example, for 1999, 1.339 thousand gallons of gasoline saved at an average price of $1.56 per gallon is $2.089 (rounded to $2 in thousands of 2012$).

Table 5-13. Gallons of Gasoline Saved per 1,000 Miles Driven

Vehicle Type	Fuel Economy	Gallons Saved per 1,000 Miles Driven
ICV	23.5 miles per gallon	N/A
HEV	34.8 miles per gallon	13.8[a]
PHEV	40.8 miles per gallon equivalent	18.1
EV	82.3 miles per gallon equivalent	30.4

[a] Gallons saved per 1,000 miles are derived from fuel economy as follows: 13.8 = 1,000((1/23.5) − (1/34.8)). Likewise, 30.4 = 1,000((1/23.5) − (1/82.3)).

Source: Average fuel economy for ICVs, HEVs, and EVs comes from Huo, Wu, and Wang (2009, p. 1798). Fuel economy for PHEV is a weighted average of HEV and EV fuel economy based on the assumption that a PHEV operates in charge-depleting mode (comparable to EV) for 25.6 percent of its miles driven and in charge-sustaining mode (comparable to HEV) for 74.4 percent of its miles driven. This assumption comes from the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model, developed by Argonne National Laboratory. PHEV fuel economy was therefore calculated as a miles-weighted average of gallons per mile: 40.8 = 1/((0.256)(1/82.3) + (0.744)(1/34.8)).

Table 5-14. Inflation-Adjusted Price of Gasoline per Gallon, by Year

Year	(1) Average Weekly U.S. Price per Gallon, All Grades	(2) Price Index (2012 = 100)	(3) Average Price per Gallon (2012$)
1999	1.18	75.3	1.56
2000	1.52	76.9	1.98
2001	1.46	78.6	1.86
2002	1.39	79.9	1.73
2003	1.60	81.6	1.96
2004	1.89	83.9	2.26
2005	2.31	86.7	2.67
2006	2.62	89.5	2.93
2007	2.84	92.1	3.09
2008	3.30	94.1	3.51
2009	2.41	94.9	2.53
2010	2.84	96.2	2.95
2011	3.58	98.3	3.64
2012	3.68	100.0	3.68

Note: The inflation-adjusted per gallon price of gasoline is assumed to stay at the 2012 value through 2022.

Source: Column (1) from http://www.eia.gov/oil_gas/petroleum/data_publications/wrgp/ mogas_history.html; Column (2) from Table A-2.

The fuel savings impacts in column (7) and the inflation-adjusted fuel cost savings in column (8) of Table 5-12 represent the energy and resource benefits quantified in this evaluation. Thus, VTO's R&D investments saved or will ultimately save

- 1.0 billion gallons of gasoline valued at $3.3 billion (2012$) from 1992 through 2012 and
- 2.1 billion gallons of gasoline valued at $7.3 billion (2012$) from 1992 through 2022, accounting for the remaining useful lives of EDVs on the road by the end of 2012.

6 Environmental and Energy Security Benefits

On-road operation of EDVs powered by NiMH and Li-ion battery technologies is more efficient than on-road operation of conventional ICVs, consuming less gasoline and emitting fewer air pollutants per mile traveled. This section presents estimates of the environmental and energy security impacts from the on-road operation of EDVs.

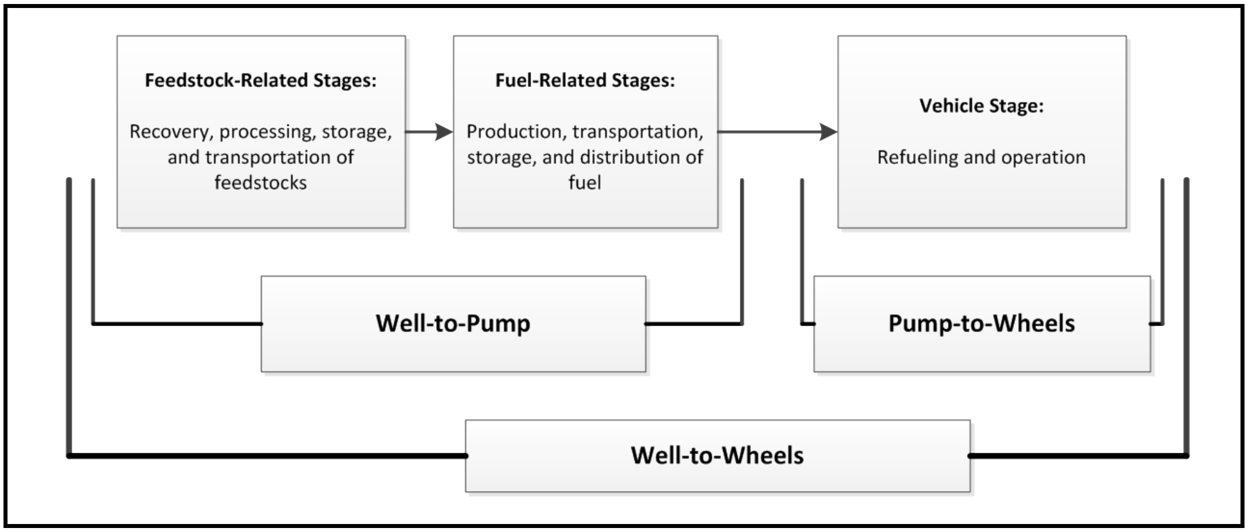
As in Section 5, for continuity of argument and analysis, the calculation of results for 1999 through 2012 and 1999 through 2022 is provided in this section. However, the calculation of economic performance measures is provided for these two time periods in Sections 8 and 9, respectively.

6.1 APPROACH TO AVOIDED EMISSIONS ESTIMATION

Emissions from vehicles can be divided into two parts: well-to-pump (WtP) and pump-to-wheels (PtW). See Figure 6-1. This evaluation quantifies the PtW, or vehicle operation, emissions reductions from EDVs. For information purposes, estimates of impacts from well-to-wheel (WtW) that also account for fuel production, feedstocks, distribution, and transportation are included in Appendix G.

Under the operation of a gasoline internal combustion engine, vehicles emit a number of pollutants that contribute to air pollution, acid rain, visibility impairment, surface water pollution, and climate change (U.S. EPA, 2000). The ability of EDVs to operate on electric power for a portion or all of their operation reduces the amount of fuel combusted and therefore the amount of tailpipe emissions. Table 6-1 lists the specific pollutants relevant to this analysis.

Figure 6-1. Well-to-Wheels, Well-to-Pump, and Pump-to-Wheels Analysis for Fuel and Vehicle Systems



Source: Wu et al. (2006).

Table 6-1. Air Pollutants Considered in this Evaluation

Name	Abbreviation	Type
Carbon dioxide	CO_2	Greenhouse gas
Methane	CH_4	Greenhouse gas
Nitrous oxide	N_2O	Greenhouse gas
Carbon monoxide	CO	Air pollutant that can oxidize into a greenhouse gas[a]
Volatile organic compounds	VOC	Air pollutant that can oxidize into a greenhouse gas[a]
Nitrogen oxides	NO_x	Air pollutant
Particulate matter smaller than or equal to 2.5 micrometers	$PM_{2.5}$	Air pollutant
Sulfur dioxide	SO_2	Air pollutant
Ammonia	NH_3	Air pollutant

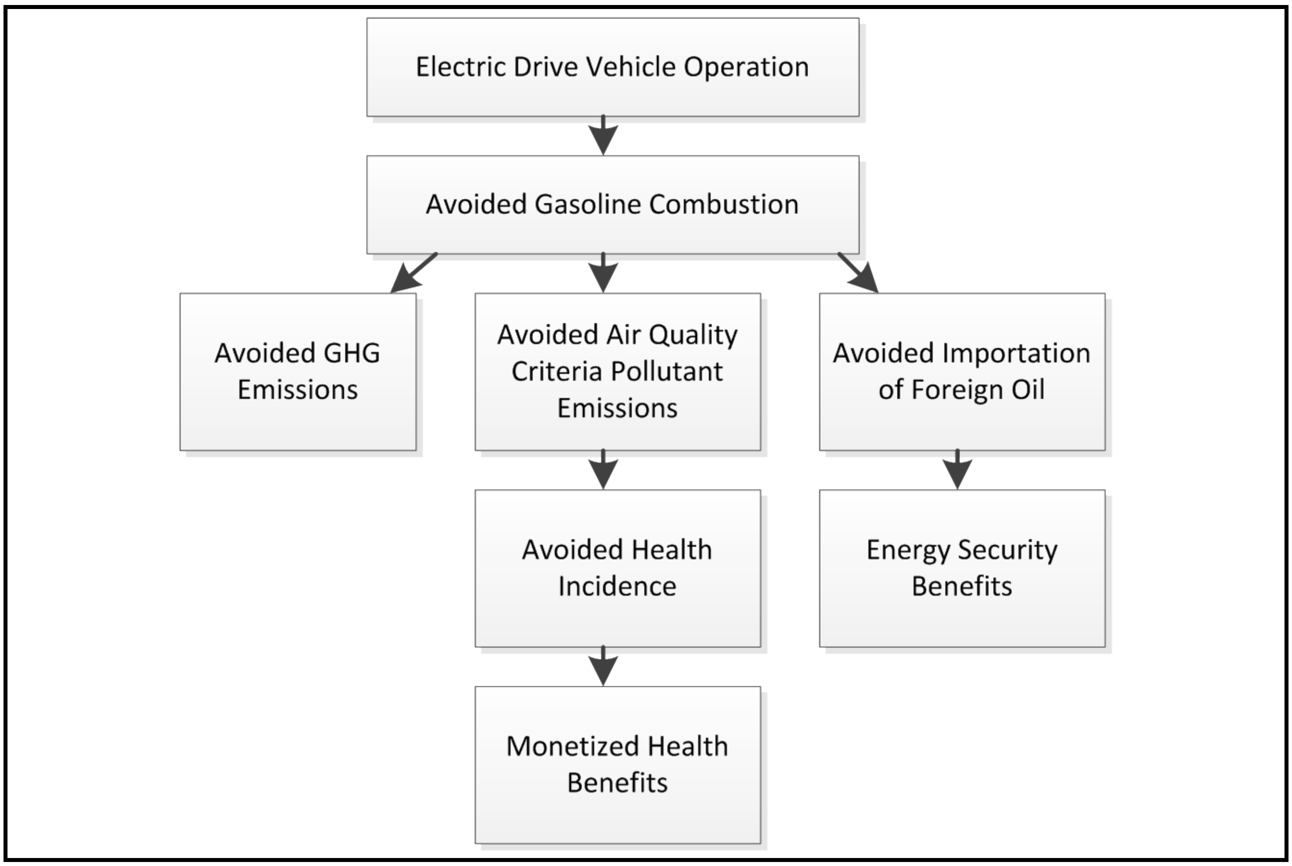
[a] The carbon contained in CO and VOCs can oxidize into CO_2 (ANL, 2012). Sources: U.S. EPA (2012a, 2012e).

Under the operation of an internal combustion engine, vehicles emit a number of pollutants that contribute to air pollution, acid rain, visibility impairment, surface water pollution, and climate change.

The impacts of EDVs on greenhouse gas (GHG) emissions, changes in the incidence of adverse health events from changes in air quality, and changes in energy security from reduced oil importation are based on the following assumptions (see Figure 6-2):

- Each HEV, PHEV, or EV purchase offsets the purchase of a new ICV in any given year.
- All vehicle types use a fuel blend of 90.5% reformulated gasoline and 9.5% ethanol.[29]
- Emissions from brake and tire wear do not change by vehicle type.

Figure 6-2. Approach for Assessing Environmental Health Benefits and Energy Security Impacts



[29] According to DOE (2013), over 95% of U.S. gasoline contains up to 10% ethanol, or E10.

The Greenhouse Gases, Regulatory Emissions, and Energy Use in Transportation (GREET) model, developed by Argonne National Laboratory, was used to estimate emissions changes. The GREET model estimates emissions factors for each vehicle type (ICV, HEV, PHEV, and EV) in 5-year intervals called vehicle model years. GREET provides emissions factors for GHGs and common air pollutants.

In 2000, the U.S. EPA instituted Tier 2 requirements, which required reductions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) emissions as well as lower sulfur content in gasoline for all vehicles. These requirements were phased in throughout the mid-2000s (U.S. EPA, 2000). To account for this adjustment in the analyses that follow, it was assumed that all vehicles purchased in 2005 and before possess the emissions factors from the GREET 2005 vehicle model year. All vehicles sold between 2006 and 2012 were assumed to possess the emissions factors of the GREET 2010 vehicle model year.[30] Figure 6-2 provides an overview of the methodology for this section.

6.2 AVOIDED GREENHOUSE GAS EMISSIONS

The three GHGs produced during fossil fuel combustion are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).[31] Each has a differing impact depending on the gases' ability to absorb energy and how long the gas remains in the atmosphere. This is called the global warming potential (GWP). GWP is measured in equivalents of a metric ton of CO_2. Gasoline combustion emits far fewer quantities of CH_4 and N_2O than CO_2, however, CH_4 and N_2O are more effective at trapping heat in the atmosphere. Thus, they both have a higher GWP than CO_2. CH_4 and N_2O contribute 20 and 300 times, respectively, more to global warming than CO_2 (U.S. EPA, 2012a).

[30] Because PHEV and EVs were not introduced to the market until 2011, only the GREET 2010 model year estimates were used for these vehicle types. This assumption will account for the greater avoided reductions associated with early HEV models before the U.S. EPA's regulations took effect on all vehicles. See http://greet.es.anl.gov.

[31] Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are also considered GHGs. However, these are not directly associated with fossil fuel combustion and therefore are not included in this analysis.

The GREET model is used to estimate the rate of GHG emissions per mile driven for each vehicle type. Emissions reduction potential varies by EDV type because an HEV operates using its gasoline engine more than a PHEV, while an EV will have zero tailpipe emissions because it does not use a gasoline engine. The GREET model estimates a GHG emissions factor that captures the emissions of CO_2, CH_4, N_2O, and the carbon contained in VOCs and carbon monoxide (CO) that will fully oxidize into CO_2. This GHG estimate is measured in metric tons of equivalent CO_2 and accounts for the higher GWP of the non-CO_2 gases. Table 6-2 lists the emissions factors of GHGs by vehicle type and model year.

To calculate GHG emissions, fuel savings impacts from Table 5-12 were separated into the appropriate model year and vehicle type (see Table 6-3). Then, GHG emissions reductions were calculated by multiplying the equivalent mileage by the difference in emissions between the appropriate vehicle type and a conventional ICV.

For example, in 1999 HEVs were driven 97,000 miles. This value was multiplied by 97.2 (the emissions factor of an ICV [337.2] subtracted from the emissions factor of an HEV [240.4]) and then converted to metric tons.

Figure 6-3 and Table 6-4 present the avoided GHG emissions results. For 1999 through 2012, nearly 7 million metric tons of CO_2eq were avoided. When accounting for the full effective useful life of vehicles on the road as of the end of 2012, the emission of 14.5 million metric tons of CO_2eq is estimated to be avoided by the end of 2022.

Table 6-2. Pump-to-Wheels Greenhouse Gas Emissions Factors (g/mile)

	(1) ICV	(2) HEV	(3) PHEV	(4) EV
Models 1999–2005				
CO_2 equivalent	337.6	240.4		
Models 2006–2012				
CO_2 equivalent	318.7	227.0	163.1	0.0

Source: ANL (2012).

Table 6-3. Miles Driven by Vehicle Type

Year	(1) HEV (model years 1999–2005; thousands)	(2) HEV (model years 2006–2012; thousands)	(3) PHEV (thousands)	(4) EV (thousands)
1999	97			
2000	58,895			
2001	195,901			
2002	449,485			
2003	788,913			
2004	1,393,754			
2005	2,877,430			
2006	2,831,428	1,801,438		
2007	2,716,885	4,201,413		
2008	2,575,146	6,161,156		
2009	2,511,419	7,667,531		
2010	2,448,924	8,888,168		
2011	2,316,902	9,987,442	39,099	51,735
2012	2,140,903	11,784,928	225,450	122,442
2013	1,862,932	11,479,579	225,385	121,129
2014	1,528,189	11,086,580	216,040	114,893
2015	880,970	10,692,307	201,471	108,484
2016		10,115,326	196,524	106,227
2017		8,445,693	193,353	103,869
2018		6,519,018	186,972	100,942
2019		4,933,139	182,880	97,979
2020		3,563,269	175,340	94,742
2021		2,411,963	166,038	84,273
2022		1,219,271	108,276	40,933
1999–2012	23,306,083	50,492,075	264,549	174,176
1999–2022	27,578,175	120,958,220	2,116,827	1,147,649

Note: See also Table 5-12. HEVs were broken out by model years beginning in 2006.

Figure 6-3. Pump-to-Wheel Avoided Greenhouse Gas Emissions (thousands of metric tons of CO_2eq)

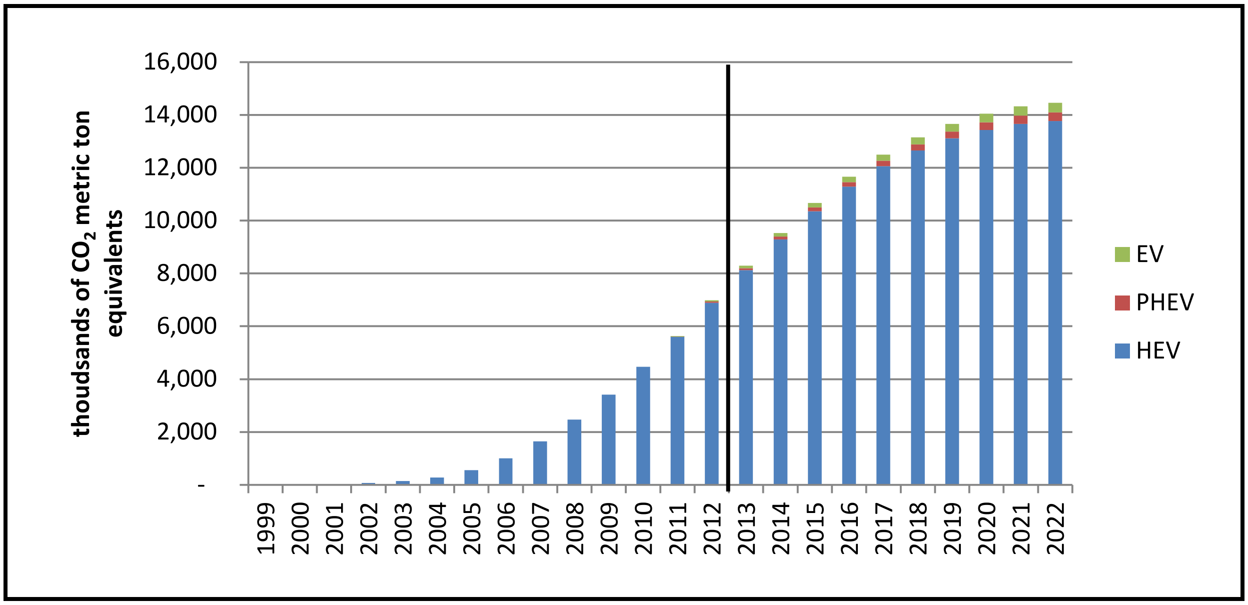


Table 6-4. Pump-to-Wheel Avoided Greenhouse Gas Emissions, by Vehicle Type (thousands of metric tons of CO_2eq)

	1999–2012	1999–2022
HEV	6,893	13,766
PHEV	41	329
EV	55	366
Total	6,989	14,461

EDVs were responsible for avoiding nearly 7 million metric tons of CO2eq from 1999 through 2012. When accounting for the full effective useful life of vehicles on the road as of the end of 2012, the emission of 14.5 million metric tons of CO2eq is estimated to be avoided by the end of 2022.

The U.S. EPA's Greenhouse Gas Equivalency Calculator was used to convert these estimates of CO_2eq into everyday terms (U.S. EPA, 2012b). The avoided 14.5 million metric tons of CO_2eq emissions from throughout the life-cycle time series is the equivalent of the

- GHG emissions from the electricity used by 2,164,827 homes for 1 year,
- carbon sequestered annually by 11,853,313 acres of U.S. forests, and
- annual CO_2 emissions of 4.1 coal-fired power plants.

The majority of the avoided GHG emissions come from HEVs. Although PHEVs and EVs have significantly lower PtW GHG emissions than HEVs, these vehicles only account for a small percentage of the GHG reductions because only 2 years of these vehicles' operation are included in our analysis.

Current efforts are underway to account for the economic impact of climate change damages such as declined agricultural productivity or property damages from extreme weather events (U.S. EPA, 2012c). The retrospective values of the Social Cost of Carbon, for nonregulatory analysis purposes, are still in their early stages of development. For this study, reductions in GHG emissions are not monetized. However, for the future, units of CO_2 and other GHG emissions may have monetary value based on social cost and/or CO_2 mitigation policies.

6.3 AVOIDED NON-GHG AIR POLLUTANT EMISSIONS

VOCs and NO_x from gasoline combustion interact in the lower atmosphere to form ambient ozone, which in high levels can exacerbate existing respiratory illness (such as asthma) and over the long term may cause lung damage.

Non-GHG air pollutants do not trap heat in the atmosphere; however, they contribute to ozone and particulate matter (PM) pollution, which can negatively affect air quality and thus human health (U.S. EPA, 2012e).[32] For example, VOCs and NO_x interact in the lower atmosphere to form ambient ozone, which in high levels can exacerbate existing respiratory illness (such as asthma) and over the long term may cause lung damage (U.S. EPA, 2000).

Avoided emissions of VOCs, NO_x, PM smaller than or equal to 2.5 micrometers ($PM_{2.5}$), sulfur dioxide (SO_2), and ammonia (NH_3) from the fuel savings impacts were estimated. Although we estimate national impacts without consideration for regional issues, the majority of EDVs are purchased and operated in urban environments where air quality improvements are needed most. Thus, the analysis may underestimate actual impacts.[33]

Emissions factors from the GREET model were used to determine avoided emissions in short tons. Similar to the GHG

[32] Ozone and PM also affect the environment through reduced visibility, reduction in agricultural and forestry yields, increased acid deposition, and increased eutrophication and nitrification of surface waters (U.S. EPA, 2000). For the purposes of this study, only the impacts on human health were monetized.

[33] Huo, Wu, and Wang (2009) found that HEVs and EVs can reduce emissions compared with ICVs of VOC, NO_x, and $PM_{2.5}$ at a higher percentage in urban areas than when applied to a national model.

emissions calculated above, these emissions factors depend on vehicle type and model year (see Table 6-5). An estimate of NH_3 was provided from the U.S. EPA (2013) MOVES2010b model for an ICV, and reductions in NH_3 for EDVs were scaled based on the percentage reduction of VOCs (about 54% for HEVs) from the GREET model.

To calculate avoided emissions of pollutants, mileage estimates from Table 6-2 were multiplied by the difference in emissions between HEV, PHEV, and EVs and ICVs (Table 6-6).[34]

Table 6-5. Pump-to-Wheels Emissions Factors (mg/mile)

	(1) ICV	(2) HEV	(3) PHEV	(4) EV
Models 1999–2005				
VOC [a]	122.0	65.9		
NO_x	141.0	118.4		
$PM_{2.5}$	7.5	7.5		
VOC_{evap}	58.0	58.0		
SO_2 [b]	5.6	4.0		
NH_3	17.0	9.2		
Models 2006–2012				
VOC	95.0	51.3	31.1	0.0
NO_x	69.0	58.0	35.1	0.0
$PM_{2.5}$	7.5	7.5	4.5	0.0
VOC_{evap}	57.0	57.0	34.6	0.0
SO_2	5.3	3.8	2.7	0.0
NH_3	17.0	9.2	5.6	0.0

[a] VOC emissions were derived from two sources: the emissions from vehicle exhaust and from the evaporation of gasoline in the fuel system (U.S. EPA, 2000). These emissions are listed separately in this table and then are combined for an estimate of total avoided VOC emissions in subsequent tables.

[b] Emissions factors for SO_x were used as a proxy for SO_2 as for most combustion processes in GREET. SO_x is nearly 100% SO_2.

Source: ANL (2012) and U.S. EPA (2013).

[34] Similar to GHG emissions, there are concerns that the WtP emissions associated with the fuel source used for charging PHEVs and EVs may cause there to be a negative impact on the WtW emissions of these air quality pollutants. For example, if the electricity fuel source is a coal-fired power plant, then SO_2 emissions in the WtP stage may be higher for a PHEV or EV than a conventional ICV and could increase overall emissions.

Table 6-6. Pump-to-Wheels Avoided Emissions (short tons)

	(1) VOC	(2) NO_x	(3) $PM_{2.5}$	(4) SO_2	(5) NH_3
1999	0	0		0	0
2000	4	1		0	1
2001	12	5		0	2
2002	28	11		1	4
2003	49	20		1	7
2004	86	35		2	12
2005	178	72		5	25
2006	262	92		8	40
2007	370	119		12	60
2008	456	139		15	75
2009	525	156		17	88
2010	580	169		19	98
2011	637	185	1	21	108
2012	742	214	2	25	125
2013	710	204	2	24	120
2014	668	190	2	23	114
2015	607	168	2	21	104
2016	524	139	2	18	92
2017	443	118	1	15	77
2018	349	94	1	12	60
2019	271	74	1	9	47
2020	204	57	1	7	35
2021	146	42	1	5	24
2022	76	22	1	3	13
1999–2012	3,928	1,217	2	128	643
1999–2022	7,926	2,324	16	265	1,329

Note: Sums may not add to totals because of independent rounding.

The majority of emissions reductions come in the form of VOC and NO_x reductions with 7,926 and 2,324 short tons avoided, respectively. Reductions in $PM_{2.5}$ were small because only PHEVs and EVs were estimated to reduce $PM_{2.5}$ emissions in the PtW stage (see Table 6-7).

Table 6-7. Pump-to-Wheels Avoided Emissions, by Vehicle Type (short tons)

	(1) VOC	(2) NO_x	(3) $PM_{2.5}$	(4) SO_2	(5) NH_3
Retrospective (1999–2012)					
HEV	3,874	1,194		126	636
PHEV	25	10	1	1	3
EV	29	13	1	1	3
Total	3,928	1,217	2	128	643
Life Cycle (1999–2022)					
HEV	7,533	2,158		252	1,280
PHEV	201	79	7	6	27
EV	192	87	9	7	22
Total	7,926	2,324	16	265	1,329

Note: Sums may not add to totals because of independent rounding.

6.4 ENVIRONMENTAL HEALTH BENEFITS

EPA's COBRA model was used to quantify and monetize the changes in the incidence of adverse health events associated with emissions reductions. COBRA converts inputs of emissions changes in air pollution into changes in health effects and calculates the economic value of these changes.

EPA's COBRA model was used to quantify and monetize the value of changes in the incidence of avoided adverse health events associated with emissions reductions. COBRA converts inputs of emissions changes in air pollution into changes in health incidents and calculates the economic value of these changes (U.S. EPA, 2012d; O'Connor et al., 2013). These impacts are termed environmental health benefits. A summary discussion of COBRA is included in Appendix G.

COBRA's baseline estimates of health impacts and their value are based on projected air quality, population, and income for 2017. For each year, the PtW avoided emissions from Table 6-6 were inputs into the COBRA model. To adapt COBRA for this retrospective analysis, the number of health incidents was scaled for each year to reflect changes in the national resident population based on U.S. Census estimates through 2012. The resident population from 2013 through 2022 was estimated by applying the percentage changes in population from the 2013 Annual Energy Outlook to the 2012 population estimate from the U.S. Census.

Several valuation endpoints in COBRA, including the value placed on premature mortality, are adjusted over time based on projected changes in income and elasticity estimates for how willingness to pay for health outcomes will change with time. The 2017 value for health incidents was adjusted to the years in this analysis based on COBRA's elasticity estimates and per capita real GDP changes based on Bureau of Economic Analysis estimates through 2012. Income changes from 2013 through 2022 were estimated by applying the percentage changes in per capita real GDP from the 2013 Annual Energy Outlook to BEA's 2012 per capita real GDP estimate.

Table 6-8 shows the avoided incidence and their economic value for 2012. COBRA produces high and low estimates of the value of total health benefits based on two different sets of assumptions for the impact of ambient $PM_{2.5}$ on adult mortality and nonfatal heart attacks. For adult mortality and nonfatal heart attacks, benefits or costs are expected to continue in future years; therefore, COBRA calculates the present value for these endpoints using either a 3% or 7% discount rate. COBRA does not report undiscounted values.

Table 6-8. Pump-to-Wheels Environmental Health Benefits, 2012

Health Effect	Avoided Incidence	Economic Value (2012$ thousands)
Adult mortality (low)	2.3	17,348
Adult mortality (high)	6.0	44,589
Infant mortality	0.0[a]	43
Nonfatal heart attacks (low)	0.3	34
Nonfatal heart attacks (high)	2.6	316
Resp. hospital admissions	0.9	26
Cardiovascular (CDV) hospital admissions	0.8	34
Acute bronchitis	3.8	2
Upper respiratory symptoms	68.4	5
Lower respiratory symptoms	47.9	2
Asthma ER visits	1.6	1
Minor restricted activity days (MRAD)	2,114.6	147
Work loss days	357.3	56
Asthma exacerbations	71.9	8
Total		$17,706 (Low) $45,229 (High)

[a] COBRA rounded the incidence value to zero from a very small value, however, because the high monetary value associated with prolonging life, even a very small value, produces some cost.

PtW stage health benefits totaled between approximately $88.2 and $225.3 million for 1999 through 2012 (midpoint, $157 million) and between $192.0 and $490.6 million for 1999 through 2022 (midpoint, $341 million).

In 2012 alone, the economic value of avoided incidence is estimated to be between $17.7 and $45.0 million using a 7% discount rate. The majority of these benefits come from avoided mortality, estimated to be between $17.3 and $44.6 million. The full time series is presented in Table 6-9; however, the mean of the low and high values is used in the economic analysis in Sections 8 and 9.

PtW stage health benefits totaled between approximately $88.2 and $225.3 million for 1999 through 2012 (midpoint, $157 million) and between $192.0 and $490.6 million for 1999 through 2022 (midpoint, $341 million). An assessment of WtW health benefits is presented for reference in Appendix G. The avoided adverse health event incidence estimates are in Table 6-10.

Table 6-9. Pump-to-Wheels Time Series of Environmental Health Benefits, 1999–2022

Year	(1) EDV Miles Driven[a] (thousands)	(2) U.S. Resident Population[b] (thousands)	(3) Environmental Health Benefits (low; 2012$ thousands)	(4) Environmental Health Benefits (high; 2012$ thousands)
1999	97	279,040	0	0
2000	58,895	282,162	68	174
2001	195,901	284,969	229	584
2002	449,485	287,625	531	1,357
2003	788,913	290,108	946	2,416
2004	1,393,754	292,805	1,703	4,351
2005	2,877,430	295,517	3,578	9,140
2006	4,632,866	298,380	5,548	14,172
2007	6,918,298	301,231	8,133	20,776
2008	8,736,302	304,094	10,169	25,975
2009	10,178,950	306,772	11,684	29,844
2010	11,337,092	309,326	13,140	33,563
2011	12,395,177	311,588	14,757	37,695
2012	14,273,723	313,914	17,706	45,229
2013	13,689,024	316,969	17,183	43,894
2014	12,945,702	320,051	16,492	42,129
2015	11,883,232	323,156	15,349	39,209
2016	10,418,077	326,283	13,634	34,830
2017	8,742,915	329,427	11,766	30,057
2018	6,806,933	332,586	9,475	24,206

(continued)

Table 6-9. Pump-to-Wheels Time Series of Environmental Health Benefits, 1999–2022 (continued)

Year	(1) EDV Miles Driven[a] (in thousands)	(2) U.S. Resident Population[b] (in thousands)	(3) Environmental Health Benefits (low; 2012$ thousands)	(4) Environmental Health Benefits (high; 2012$ thousands)
2019	5,213,999	335,758	7,552	19,293
2020	3,833,351	338,942	5,831	14,896
2021	2,662,274	342,133	4,289	10,958
2022	1,368,481	345,328	2,271	5,802
1999–2012[c]			88,192	225,277
1999–2022[c]			192,034	490,552

[a] Sum of all columns in Table 6-3.

[b] Source: 1999 through 2012 estimates from U.S. Census Bureau (2004, 2011, 2013). 2013 through 2022 based on percentage changes in population projected in the 2013 Annual Energy Outlook (U.S. Energy Information Administration, 2013).

[c] The COBRA model applied a 7% discount rate to the stream of benefits associated with the emissions reduction in each year. Totals are undiscounted in the sense that no further discounting is applied here. Discounted totals are presented in Section 8. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study. The average of the low and high estimates of health benefits produced by COBRA was used for this study.

Table 6-10. Avoided Adverse Health Incidence Associated with Fuel Savings, 1999-2022

Incidence	1999–2012	1999–2022	Unit of Measure
Avoided mortality[a]	20.04	42.39	Deaths
Avoided infant mortality[a]	0.02	0.05	Deaths
Avoided nonfatal heart attacks	6.96	14.73	Attacks
Avoided resp. hospital admissions.	4.34	9.17	Admissions
Avoided CDV hospital admissions	4.05	8.57	Admissions
Avoided acute bronchitis	18.24	38.57	Cases
Avoided upper respiratory symptoms	331.47	701.04	Episodes
Avoided lower respiratory symptoms	232.31	491.31	Episodes
Avoided asthma ER visits	7.79	16.48	Visits
Avoided MRAD	10,265.31	21,710.22	Incidences
Avoided work loss days	1,734.48	3,668.28	Days
Avoided asthma exacerbations	348.78	737.64	Episodes

[a] Researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Krewski et al. (2009) and Laden et al. (2006). COBRA includes different mortality risk estimates for both adults and infants.

6.5 ENERGY SECURITY BENEFITS

Fuel savings can lead to a reduced requirement for foreign oil importation, which may lessen the risk of oil disruptions and exogenous price shocks. The number of barrels of foreign oil avoided across the time series was estimated under the assumption that each marginal barrel of oil avoided is composed of oil sourced from the same locations as total consumption (see Table 6-11).

Table 6-11. Pump-to-Wheels Energy Security Benefits

Year	(1) Gallons of Gasoline Avoided[a] (thousands)	(2) Barrels of Oil Avoided[b] (thousands)	(3) Percentage of Net Foreign Oil Imports[c]	(4) Barrels of Foreign Oil Avoided (thousands)
1999	1	0	51	0
2000	814	43	53	23
2001	2,707	142	55	79
2002	6,211	327	53	174
2003	10,901	574	56	322
2004	19,258	1,014	58	592
2005	39,759	2,093	60	1,262
2006	64,015	3,369	60	2,017
2007	95,594	5,031	58	2,924
2008	120,714	6,353	57	3,612
2009	140,648	7,403	51	3,804
2010	156,651	8,245	49	4,053
2011	172,295	9,068	45	4,051
2012	200,216	10,538	41	4,314
2013	192,115	10,111	39	3,916
2014	181,701	9,563	36	3,436
2015	166,852	8,782	36	3,157
2016	146,549	7,713	35	2,684
2017	123,349	6,492	35	2,249
2018	96,523	5,080	34	1,750

(continued)

Table 6-11. Pump-to-Wheels Energy Security Benefits (continued)

Year	(1) Gallons of Gasoline Avoided[a] (thousands)	(2) Barrels of Oil Avoided[b] (thousands)	(3) Percentage of Net Foreign Oil Imports[c]	(4) Barrels of Foreign Oil Avoided (thousands)
2019	74,446	3,918	34	1,338
2020	55,283	2,910	34	997
2021	38,889	2,047	35	708
2022	20,048	1,055	35	372
1999–2012	1,029,784	54,199		27,226
1999–2022	2,125,539	111,870		47,834

[a] Column (7) from Table 5-12.
[b] According to the EIA (2012b), on average, 19 gallons of gasoline can be yielded from 1 barrel of oil.
[c] Source: EIA (2012a).

From 1999 through 2012, fuel savings from VTO's investments offset the need for approximately 27.2 million barrels of foreign oil. For 1999 through 2022, the amount is 47.8 million barrels of foreign oil. These energy security benefits are not included in the economic analysis because there is presently no consensus about estimates of a so-called oil importation premium to use to monetize energy security benefits.

7 Knowledge Benefits

Section 7 and accompanying Appendix H were contributed by Rosalie Ruegg of TIA Consulting, Inc. and Patrick Thomas of 1790 Analytics LLC.

This section investigates explicit knowledge benefits of VTO's investment in Li-ion and NiMH battery research and ultracapacitors by identifying VTO's outputs of patents and publications, and tracing citations.[35] Patents indicate that something new has been invented. Both patents and publications capture knowledge and make it available to others. Citations of patents and publications show a dissemination of knowledge and a potential influence of that knowledge on subsequent innovation.

The concept underlying patent citation analysis is that the front page of a patent document contains a listing of "prior art" citations that helps to show the state of the art at the time of the patent application. The listing also demonstrates how the new patented invention is original over the prior art and often reveals influential previous work. Patent citation analysis centers on the idea that patents cited by many later patents tend to contain technological information of particular interest or importance, forming a basis for new innovations and research efforts. While it is true that patent citation analysis is imperfect, numerous validation studies have revealed the existence of a strong positive relationship between patent citations and measures of technological importance and commercial value. Patents, in fact, are widely considered to

[35] Tacit knowledge outputs, such as human capital embodied in researchers, are also invaluable knowledge benefits but are challenging to identify, trace, and assess; priority was given in this treatment to explicit knowledge outputs of patents and publications.

comprise the most comprehensive data set available with respect to technological development.[36]

The analysis presented focuses on assessing the extent to which VTO-funded research has formed a knowledge foundation for commercial innovations in energy storage. The analysis also assesses broader influence of these knowledge outputs, extending beyond energy storage. It identifies patents that have been particularly influential as indicated by a higher than expected citation rate, and it identifies publications that appear to have influenced innovation as indicated by their citation by patents. Here the emphasis is on findings; background on the design of the assessment and details on the patent citation analysis process are provided in Appendix H.

7.1 OVERVIEW OF PRINCIPAL FINDINGS

Principal findings from the assessment of knowledge benefits are that:

- VTO-funded research as captured in patents and publications contributed to the knowledge base in energy storage, as indicated by the issue of 112 patent families in energy storage, consisting of 56 Li-ion battery patent families, 9 NiMH patent families, and 47 ultracapacitor patent families over the period 1976 to 2012, and more than 2,337 publications/presentations from 2000 to 2012.
- Although the output of VTO-patents comprises a small share of global patenting in energy storage, (e.g., less than 1% of the total on average between 2008 and 2012), VTO research has formed an influential foundation for subsequent advances in the field as evidenced by a comparatively high rate of citations by the most innovative companies in the field. This finding lends supporting evidence to the study’s conclusion that a share of the technical advances in commercial batteries for EDVs is traceable to VTO’s investment.
- A comparison of average citation rates of VTO-attributed[37] patent families with the average of leading

[36] Limitations are that not every highly cited patent is necessarily important, and not every infrequently cited patent is unimportant. Moreover, the number of citations does not provide a measure of economic value. In addition, some would argue that self-citations and examiner (versus applicant) referencing of patents as prior art may lessen the significance of observed citations.

innovative companies in the field showed VTO to rank highest. Furthermore, a sizable share of the companies' patents link back to VTO-attributed patents, indicating that commercial companies were tapping into the results of VTO's research in energy storage.

- VTO's research emphasis and related patent outputs came early in each type of energy storage technology examined, preceding the surge in innovation by other organizations, and then dropping off as company patenting increased.
- VTO-funded research has led to a large number of highly influential patents in energy storage as indicated by their high rate of citations by other patents.
- More than a dozen VTO-funded publications reporting on Li-ion battery research have provided a direct route of knowledge dissemination to battery innovators as indicated by their patents citing the VTO publications.
- VTO-attributed NiMH patents were licensed widely to commercial battery and automobile manufacturers globally, such that the VTO-funded technological advancements found their way quickly into batteries powering hybrid and electric vehicles.
- The intellectual capital developed with VTO funding was found to have a broad influence as indicated by knowledge spillovers occurring in multiple areas of application.

7.2 TRENDS IN VTO-ATTRIBUTED AND OVERALL ENERGY STORAGE PATENTING

The numbers of energy storage patent families attributed to VTO-funded research are grouped by priority year in Figure 7-1. A patent family contains all the patents and patent applications that result from the same original patent application (named the priority application). A patent family

[37] The term "VTO attributed" is used to acknowledge that VTO funded the underlying research leading to the patents (as opposed to the costs of filing and defending the patents), and that the patents resulting from VTO funding may not have been assigned to DOE. Rather, they may have been assigned to funded companies, to the organizations that operate government laboratories, or to others. Appendix H explains the several ways that patents "attributed" to VTO are identified. In contrast, when a company funds research that leads to a patent, it is assigned ownership of the patent, and the patents can be identified simply as Company X's patents.

may include patents/applications from multiple countries and also multiple patents/applications from the same country.

The priority date refers to the date of filing of the original patent around which a family of related patents is based.[38] This representation is used rather than the issue date to relate more closely patenting activity to the underlying VTO-funded research. The figure shows a large increase in VTO-attributed energy storage patents from the first 4-year period, 1988 to 1992, to the second, 1993 to 1997. It shows a leveling off in number in the third period, 1998 to 2002, followed by declines thereafter. This pattern would be expected if VTO were attempting to accelerate development of the technology in its early stages when technical barriers are high, and then pull back as private company activity in the area increases. VTO staff spoke in interviews of shifting investment from NiMH batteries to Li-ion batteries after they had brought NiMH technology to a certain level.

The overall numbers of energy storage patent families by priority year for all organizations are grouped in Figure 7-2. For both Figures 7-1 and 7-2, the numbers of energy storage patent families comprise Li-ion, NiMH, and ultracapacitors. A comparison of Figures 7-1 and 7-2 shows that the number of energy storage patent families overall dwarfs the VTO-attributed set over the entire period. It also shows that the number overall from all organizations continued to rise after VTO-attributed patenting began to fall.

[38] For explanations of how patent families are formed and of patent priority and issue dates, see Appendix H.

Figure 7-1. Number of VTO-Attributed Energy Storage (Li-ion, NiMH, and Ultracapacitor) Patent Families, by Priority Year

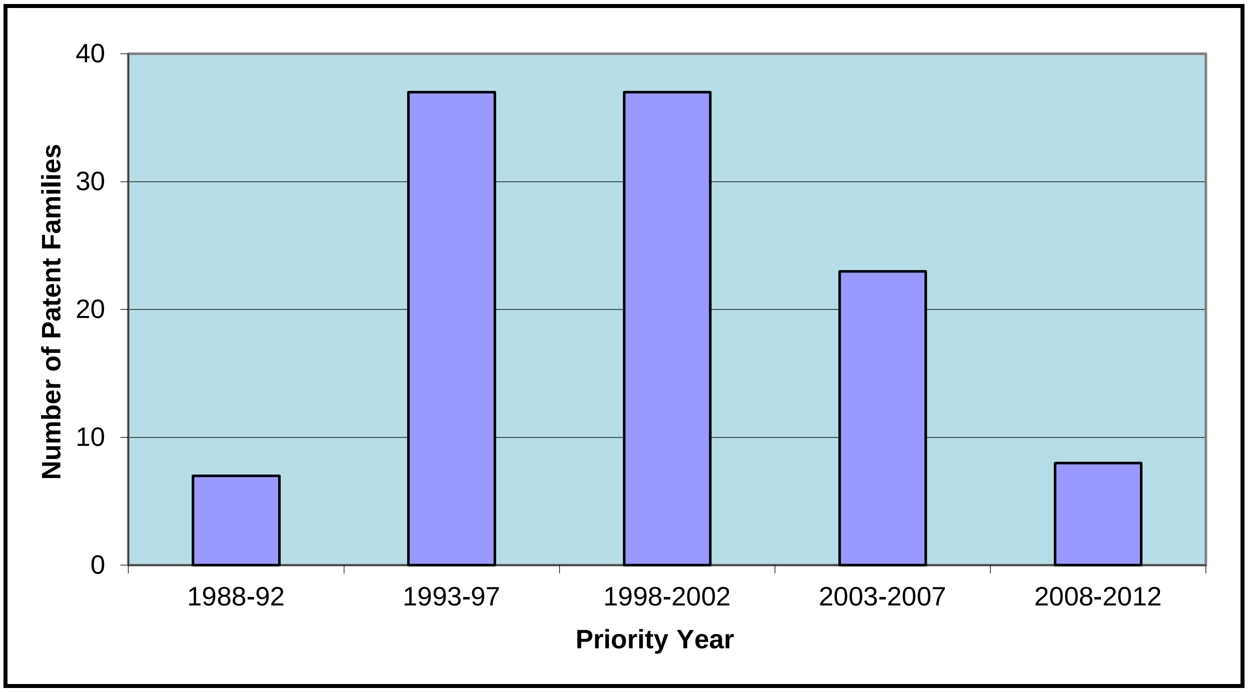
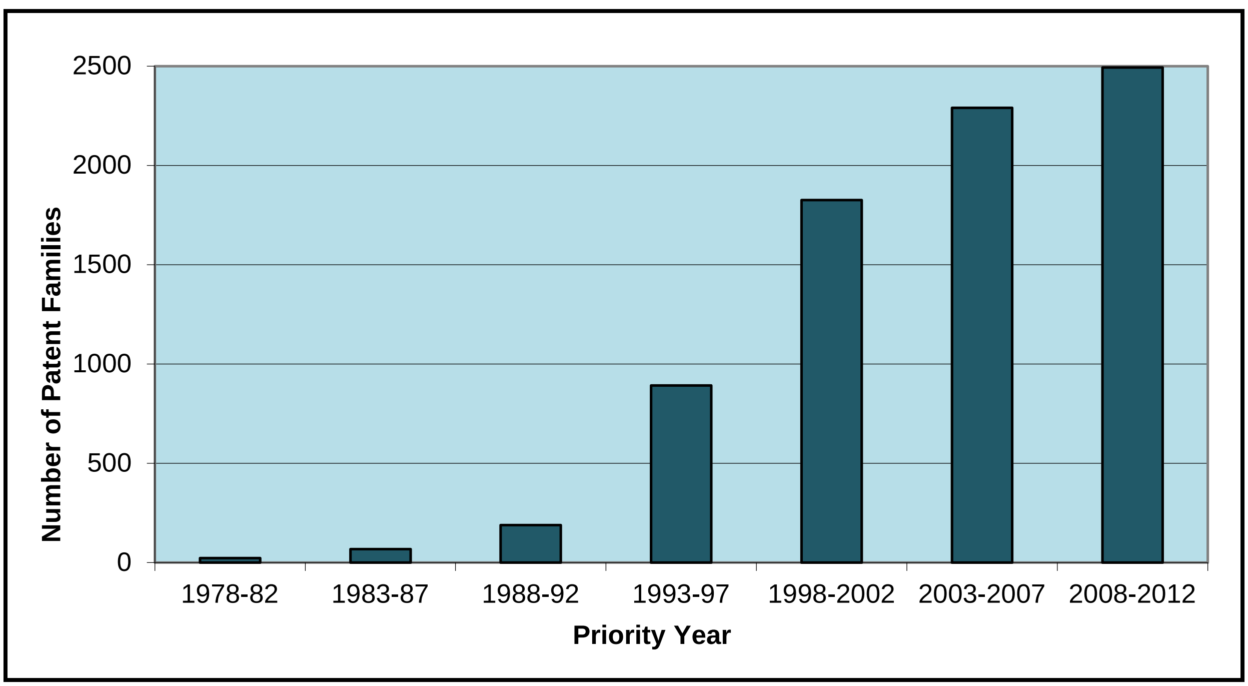


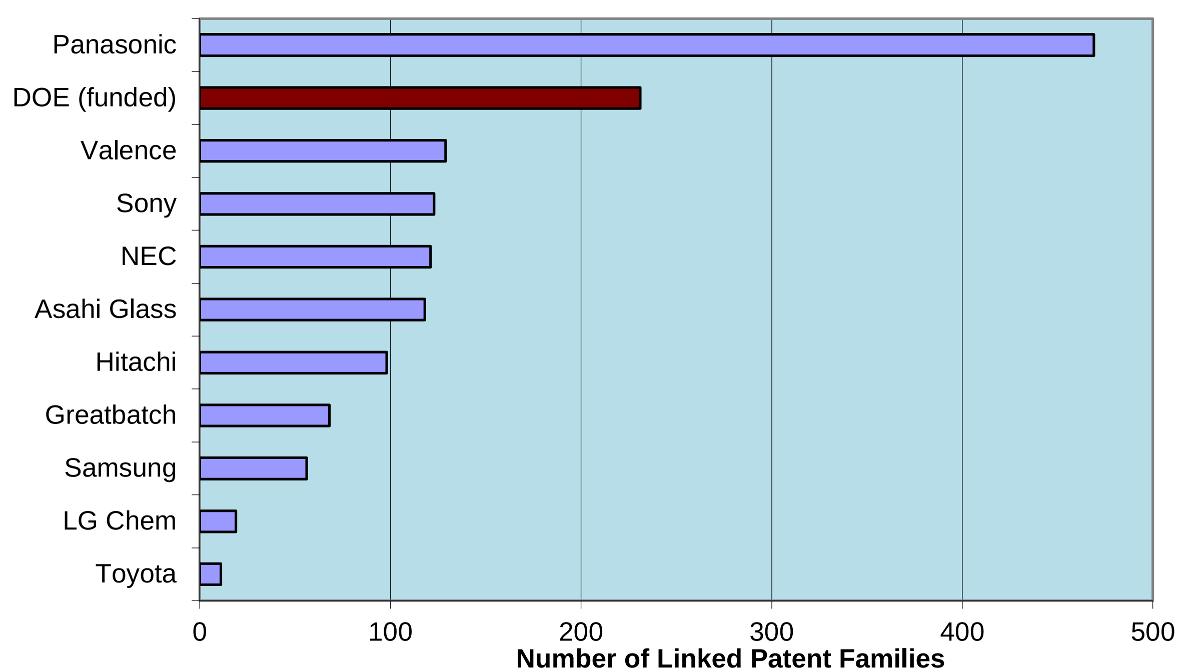
Figure 7-2. Overall Number of Energy Storage (Li-ion, NiMH, and Ultracapacitor) Patent Families for All Organizations, by Priority Year



7.3 INFLUENCE OF VTO ENERGY STORAGE PATENTS ON ENERGY STORAGE INNOVATION BY COMMERCIAL COMPANIES

Figure 7-3 depicts the comparative influence of VTO's portfolio of Li-ion, NiMH, and ultracapacitor patent families relative to that of the other organizations shown. Specifically, it shows how many of the patent families of leading company innovators in these areas are linked to earlier energy storage patent families of DOE and each of the companies. VTO is second ranked, with 231 of the leading company patent families linked to earlier VTO-attributed energy storage patents. Panasonic is first ranked. When linkages are considered, even though the VTO attributed portfolio is relatively small (e.g., 112 patent families versus Panasonic's 618), it appears that VTO's attributed patent portfolio is technically significant.

Figure 7-3. Number of Leading Companies' Energy Storage (Li-ion, NiMH, and Ultracapacitor) Patent Families Linked to Each Organization's Earlier Energy Storage Patents



Note: 231 patent families of the leading companies are linked to earlier DOE patents. It is difficult to screen only those patents attributed specifically to VTO, as opposed to DOE more broadly. Yet, most DOE-attributed Li-ion, NiMH, and ultracapacitor patents result from research funded by VTO; and the DOE patents in these fields are assumed to be VTO patents.

Figure 7-4 more clearly reveals the comparatively strong technical significance of the VTO patent portfolio by adjusting for differential portfolio size. The figure shows the average number of energy storage patent families that are linked to each earlier energy storage patent family of the organizations listed. It reflects the average influence of an organization's patent families rather than the sheer size of its portfolio. VTO is now ranked first. It has more than two subsequent patent families of the leading companies linked on average to each of its patent families. In contrast, Panasonic has an average of less than one.

It may be seen in Figure 7-5 that more than half of the leading companies had more than 10% of their energy storage patent families linked back to earlier VTO energy storage patents. Panasonic, Valence, and Asahi Glass had more than 15% of theirs linked back to earlier VTO energy storage patents.

Figure 7-4. Average Number of Leading Companies' Energy Storage Patent Families Linked to Each Earlier Energy Storage Patent Family Owned by Each Organization Listed

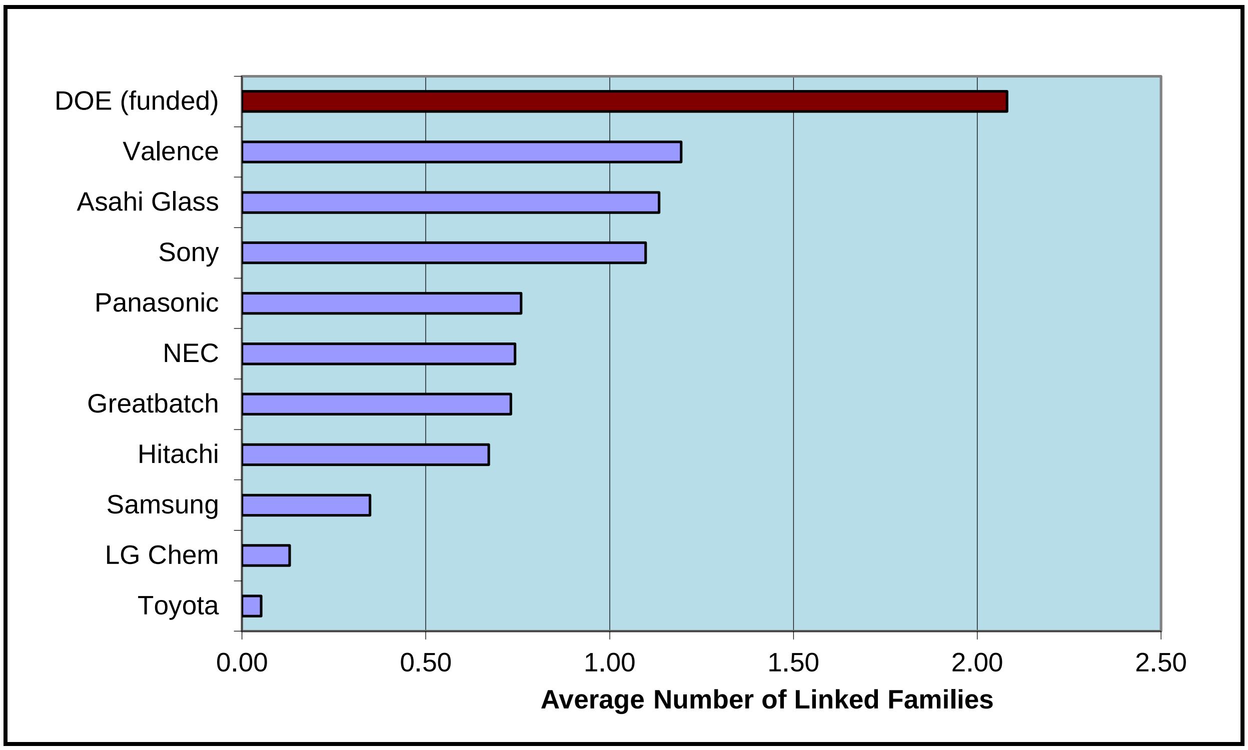
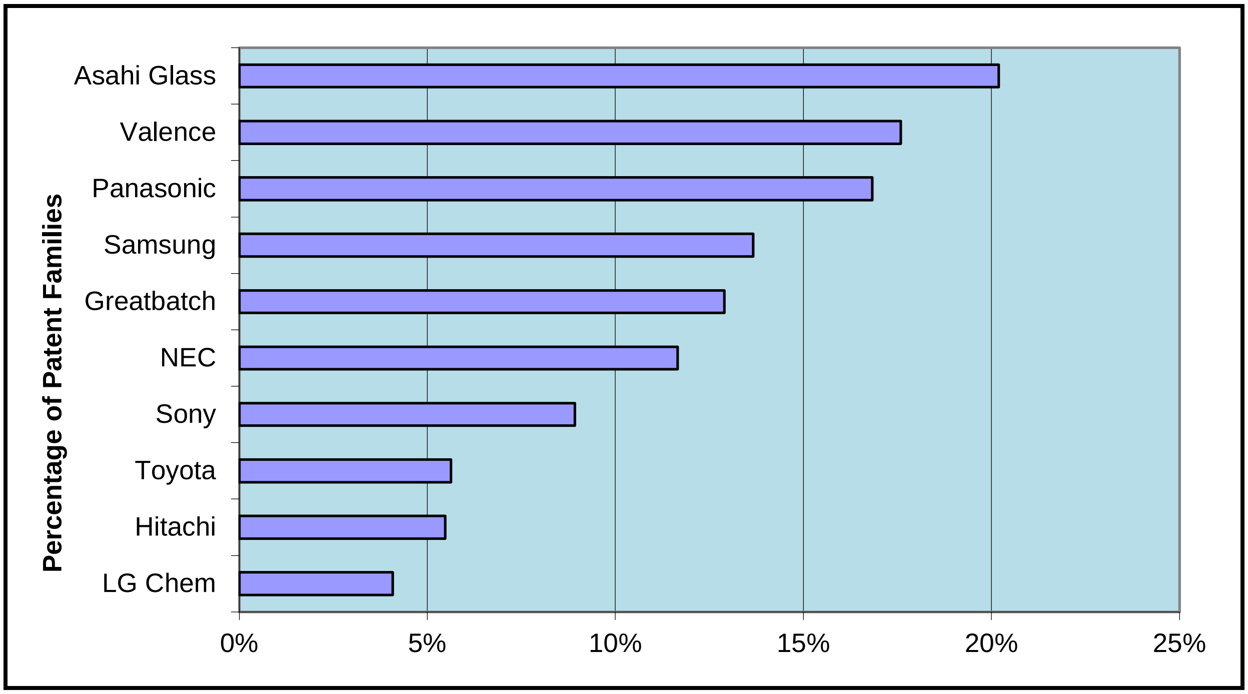


Figure 7-5. Percentage of Leading Companies' Energy Storage (Li-ion, NiMH, and Ultracapacitor) Patent Families that are Linked to Earlier VTO-Attributed Energy Storage Patents



7.4 INFLUENTIAL VTO-ATTRIBUTED ENERGY STORAGE PATENTS

This section identifies the most influential VTO-attributed patents, where heavy citing of a patent is taken as indicative that it has been particularly influential.[39] The Li-ion, NiMH, and Ultracapacitor patents most cited by leading commercial companies in each area are first identified in turn. Then VTO-attributed energy storage patents from these three subsets combined that are most heavily cited by patent families in all areas—not just energy storage—and by all organizations—not just those previously listed—are given.

Backward tracing[40] at the individual patent level identified VTO Li-ion battery patent families that are the most highly cited by Li-ion battery families of leading companies in Li-ion

[39] See Appendix H and Breitzman and Mogee (2002).

[40] As explained in Appendix H, backward tracing begins with a downstream technology/product/company focus and traces upstream to find sources of influence.

technology. They are listed in Table 7-1. The most cited is represented by anchor patent US #5219679, assigned to EIC Laboratories, and describing solid electrolytes. An anchor patent is a patent used to designate a given patent family; generally the first granted U.S. patent within a patent family is its designated anchor patent. The second describes protective lithium ion conducting ceramic coatings for lithium metal anodes, assigned to Lockheed Martin, which manages and operates the Sandia National Laboratories (via its wholly owned subsidiary, The Sandia Corporation).

Backward tracing also identified five VTO-attributed NiMH patent families highly cited by patent families of leading companies in NiMH technology. These are listed in Table 7-2. The first listed, US #5344728, attributed to VTO-funded research and assigned to ECD, alone has 79 citations by patents of the leading companies. ECD licensed its NiMH battery technology to most of the global automotive and

Table 7-1. VTO Li-ion Battery Patent Families Most Cited by Li-ion Battery Patent Families of Leading Companies in Li-ion Technology

DOE Anchor Patent	Issue Year	# Linked Leading Company Families	Assignee	Title
5219679	1993	25	EIC Laboratories	Solid electrolytes
5314765	1994	23	Lockheed Martin	Protective lithium ion conducting ceramic coating for lithium metal anodes and associate method
5426006	1995	13	Sandia	Structural microporous carbon anode for rechargeable lithium-ion batteries
6221531	2001	7	Univ. Chicago	Lithium-titanium-oxide anodes for lithium batteries
5484670	1996	7	Arizona State Univ.	Lithium ion conducting ionic electrolytes
7026071	2006	6	MIT	Non–cross-linked, amorphous, block copolymer electrolyte for batteries
5827331	1998	6	WR GRACE	Electrode compositions
6096454	2000	5	Univ. California	Surface modifications for carbon lithium intercalation anodes
5252413	1993	5	EIC Laboratories	Solid polymer electrolyte lithium batteries
5358802	1994	5	Univ. California	Doping of carbon foams for use in energy storage devices

Table 7-2. VTO-attributed NiMH Battery Patent Families Most Cited by NiMH Patent Families of Leading Companies in NiMH Technology

DOE Anchor Patent	Issue Year	# Linked Leading Company Families	Assignee	Title
5344728	1994	79	Energy Conversion Devices	Compositionally and structurally disordered multiphase nickel hydroxide positive electrode for alkaline rechargeable electrochemical cells
5506069	1996	12	Energy Conversion Devices	Electrochemical hydrogen storage alloys and batteries fabricated from Mg containing base alloys
5780184	1998	4	SAFT	Negative electrode for an alkaline cell
6335120	2002	2	Alcatel-Lucent	Non-sintered nickel electrode
5888665	1999	1	California Inst. Technology	LaNi.sub.5 is-based metal hydride electrode in Ni-MH rechargeable cells

battery companies including those in Japan and Korea. Royalty payments to DOE from licensees further confirm the linkage from commercial use of the NiMH technology back to its DOE-funded origins.

Backward tracing at the individual patent level showed more than a dozen highly cited VTO-attributed ultracapacitor patents. At the top of the list is a VTO-attributed patent assigned to Maxwell Energy, describing high performance double layer capacitors. The list is dominated by patents assigned to Maxwell Energy, University of California, and General Electric.

Forward tracing[41] identified the VTO-attributed energy storage patent families—including Li-ion, NiMH, and ultracapacitors—that have been cited by the largest number of downstream patent families—both within energy storage and more broadly and not limited to the company innovators listed previously. The patents most cited are shown in Table 7-3. At the top of the list is US #5260855, issued in 1993, assigned to the University of California (which as noted previously manages and operates Lawrence Berkeley National Laboratory), and describing supercapacitors based on carbon foams. It was cited

[41] As explained in Appendix H, forward tracing begins with an upstream area of research or invention and traces downstream to find linked innovations in all areas.

Table 7-3. VTO-Attributed Energy Storage Patent Families Linked to the Most Subsequent Patent Families in All Areas

DOE Anchor Patent	Issue Year	Total Linked Families	Linked Energy Storage Families	Other Linked Families	Assignee	Title
5260855	1993	921	173	748	Univ. California	Supercapacitors based on carbon foams
5710699	1998	839	42	797	General Electric	Power electronic interface circuits for batteries and ultracapacitors in electric vehicles and battery storage systems
5314765	1994	643	148	495	Lockheed Martin	Protective lithium ion conducting ceramic coating for lithium metal anodes and associate method
5344728	1994	636	167	469	Energy Conversion Devices	Compositionally and structurally disordered multiphase nickel hydroxide positive electrode for alkaline rechargeable electrochemical cells
5621607	1997	634	222	412	Maxwell Technologies	High performance double layer capacitors including aluminum carbon composite electrodes
5862035	1999	582	117	465	Maxwell Technologies	Multi-electrode double layer capacitor having single electrolyte seal and aluminum-impregnated carbon cloth electrodes
5827602	1998	521	80	441	Covalent Associates	Hydrophobic ionic liquids
5932185	1999	418	39	379	Univ. California	Method for making thin carbon foam electrodes
5208003	1993	371	54	317	Lockheed Martin	Microcellular carbon foam and method
5336274	1994	349	68	281	Univ. California	Method for forming a cell separator for use in bipolar-stack energy storage devices
5219679	1993	339	112	227	EIC Laboratories	Solid electrolytes
5358802	1994	314	78	236	Univ. California	Doping of carbon foams for use in energy storage devices
5420168	1995	296	12	284	Univ. California	Method of low pressure and/or evaporative drying of aerogel
5252413	1993	296	88	208	EIC Laboratories	Solid polymer electrolyte lithium batteries
5476878	1995	285	22	263	Univ. California	Organic aerogels from the sol-gel polymerization of phenolic-furfural mixtures
5426006	1995	261	58	203	Sandia Corp.	Structural micro-porous carbon anode for rechargeable lithium-ion batteries

by over 900 downstream patent families, of which 173 were in energy storage and 748 were in other areas. Second listed is a patent assigned to General Electric describing power electronic interface circuits for batteries and ultracapacitors in electric vehicles and battery storage systems. VTO-attributed patents assigned to Lockheed Martin, Energy Conversion Devices, Maxwell Technologies, Covalent Associates, EIC Laboratories, and Sandia Corporation also are among those on the list of those most cited overall.

As shown by Tables 7-1 through 7-3, VTO has funded the underlying research for a number of patents in energy storage that have been heavily cited by other patents in the field and beyond, and, on that basis, are considered influential. Furthermore, in results not shown here, VTO-attributed patents in the three energy storage technology areas covered were found to be closely linked to a number of patents of leading commercial companies that are themselves highly cited by other patents.

7.5 INFLUENCE OF VTO-ATTRIBUTED PUBLICATIONS ON INNOVATION IN ENERGY STORAGE

To identify publications coming out of VTO-funded research, a listing of energy storage publications and conference presentations was compiled from EERE's annual reports on energy storage R&D from FY2000 through FY2012. This search generated 2,337 references.[42] Because the compilation was made during a period that Li-ion research had largely displaced VTO's NiMH research, the majority of the compiled publications/presentations pertain to Li-ion battery technology. Figure 7-6 shows the distribution by year.

[42] Nonspecific listings were not counted nor were DOE internal presentations and test manuals. Of the list compiled initially, 2,281 citations were determined to have adequate information to permit searches to be performed in publication and patent databases.

Figure 7-6. VTO Publications and Presentations, by Year, 2000–2012

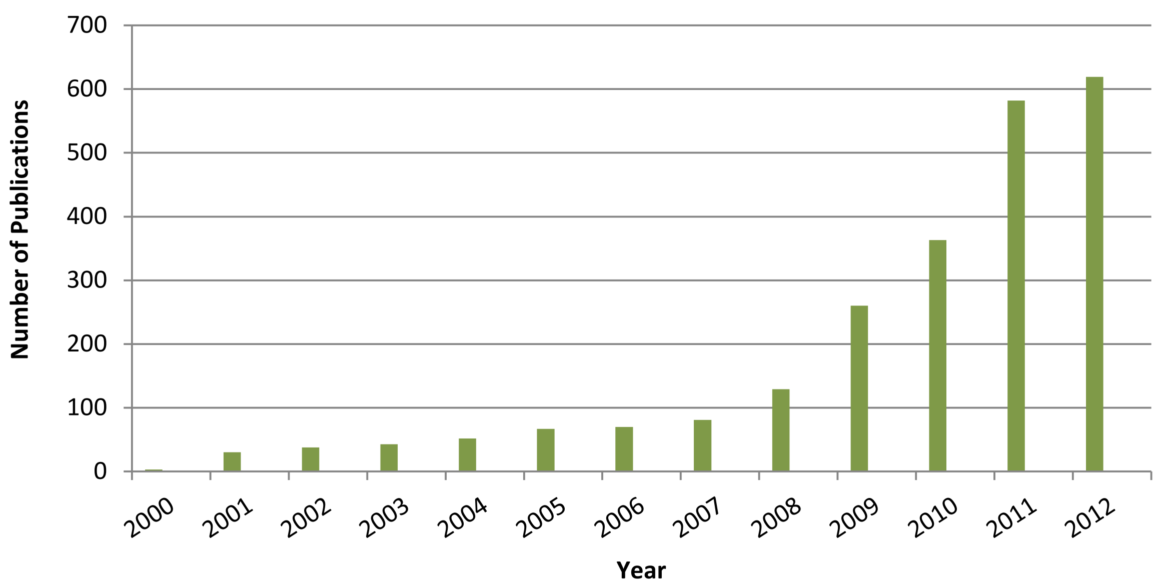


Table 7-4 lists VTO-funded journal articles found to be cited by energy storage patents as prior art. These publications may be considered foundational to the inventions described by the citing patents, and, hence, are of particular interest from the standpoint of linking knowledge creation by VTO to downstream innovation. Each of the 14 publications listed was cited by 4 to 18 patent families. Leading in patent citations was a paper by Kim, Johnson, and Thackeray, on lithium metal oxide electrodes for lithium batteries, published in *Electrochemistry Communications* in 2002. The authors were in the Electrochemical Technology Program of Argonne National Laboratory.

Table 7-4. VTO Li-ion Publications Cited by Subsequent Li-ion Patent Families as Prior Art, FY2000–2012

# Cited Patent Families	VTO Publication Reference
18	J-S. Kim, C.S. Johnson and M.M. Thackeray, “Layered xLiMO2•(1-x)Li2MO3 Electrodes for Lithium Batteries: A Study of 0.95LiMn0.5Ni0.5O2•0.05Li2TiO3,” Electrochem. Comm., 4, 205 (2002).
14	H.S. Lee, Z.F. Ma, X.Q. Yang, X. Sun, and J. McBreen, “Synthesis of a Series of Fluorinated Boronate Compounds and Their Use as Additives in Lithium Battery Electrolytes,” J. Electrochem. Soc. 151, A1429 (2004).
12	S. Yang, Y. Song, P.Y. Zavalij and M.S. Whittingham, “Reactivity, Stability and Electrochemical Behavior of Lithium Iron Phosphates,” Electrochem. Commun., 4, 234-239 (2002).
8	Wang, C.-W., Sastry, A.M., Striebel, K.A. and Zaghib, K., “Extraction of Layerwise Conductivities in Carbon- Enhanced, Multilayered LiFePO4 Cathodes,” JECS, 152, A1001 (2005).
8	D.P. Abraham, R.D. Twesten, M. Balasubramanian, I. Petrov, J. McBreen, and K. Amine, “Surface Changes on LiNi0.8Co0.2O2 Particles During Testing of High-Power Lithium-Ion Cells,” Electrochem. Commun. 8, 620 (2002).
8	J-S. Kim, C.S. Johnson and M.M. Thackeray, “Layered xLiMO2•(1-x)Li2MO3 Electrodes for Lithium Batteries: A Study of 0.95LiMn0.5Ni0.5O2•0.05Li2TiO3,” Electrochem. Comm., 4, 205 (2002).
8	Y. Song, S. Yang, P.Y. Zavalij and M.S. Whittingham, “Temperature-dependent Properties of FePO4 Cathode Materials,” Mater. Res. Bull., 37, 1249-1257 (2002).
7	A. Salah, M. Mauger, K. Zaghib, N. Ravet, J. Goodenough and J. Julien, “Fe3+ impurity reduction by carbon coating process in LiFePO4,” JECS 153, A1692 (2006).
6	M. Balasubramanian, J. McBreen, I.J. Davidson, P.S. Whitfield and I. Kargina, “In Situ X-ray Absorption Study of a Layered Manganese-Chromium Oxide Based Cathode Material,” J. Electrochem. Soc., 149, A176 (2002).
5	W-S. Yoon, K. Chung, J. McBreen, K. Zaghib, and X.Q. Yang, “Electronic Structure of the Electrochemically Delithiated Li1-xFePO4 Electrodes Investigated by P K-edge X-ray Absorption Spectroscopy” ESSL13, 9, A415 (2006).
5	J-S. Kim, C.S. Johnson, J.T. Vaughey, M.M. Thackeray, S.A. Hackney, W.C. Yoon, and C.P. Grey, “Electrochemical and Structural Properties of xLi2M’O3.(1-x)LiMn0.5Ni0.5O2 Electrodes for Lithium Batteries (M’ = Ti, Mn, Zr; 0 < x < 0.3),” Chem. Mater, 116, 1996-2006 (2004).
4	K. Amine, J. Liu & I. Belharouak, “High-temperature storage and cycling of C-LiFePO4/graphite Li-ion cells,” Electrochemistry Communications, 7, 669 (2005).
4	S-H. Kang and K. Amine, “Layered Li(Li0.2Ni0.15+0.5zCo0.10Mn0.55-0.5z)O2- zFz cathode materials for Li-ion secondary batteries,” Journal of Power Sources 146(1-2), 654-657 (2005).
4	S. Yang, P.Y. Zavalij and M.S. Whittingham, “Hydrothermal Synthesis of Lithium Iron Phosphate Cathodes,” Electrochem. Commun., 3, 505-508 (2001).

8 Retrospective Economic Performance Analysis, 1992–2012

The retrospective economic performance analysis compares monetized fuel savings and environmental health benefits with VTO investments for the period 1992 through 2012. Only monetized benefits through 2012 are compared with costs in this section. The economic performance analysis that includes the remaining effective useful lives of vehicles on the road as of December 2012 is presented in Section 9.

8.1 VTO'S R&D INVESTMENTS

The total value of VTO's R&D investments (costs) from 1992 through 2012 was $971 million. This cost overstates the relevant costs associated with the benefits measured and monetized in Sections 5 and 6.

The total value of VTO's R&D investments (costs) from 1992 through 2012 was $971 million (2012$). VTO R&D investments are in column (1) of Table 8-1 from 1992 through 2012. These costs represent VTO's total R&D investments in all areas of energy storage, including NiMH and Li-ion battery technologies. Thus, as noted previously, these investments overstate the relevant costs associated with the benefits measured and monetized in Sections 5 and 6.

Column (2) and column (3) in Table 8-1 show the present value of VTO's R&D investments, discounted to January 1, 1992, by both a 7% and a 3% discount rate, respectively. The present value at 7% was $492 million and at 3% was $703 million.

As a reminder from Section 4, the tables in this section include the 3% discount rate for informational purposes; per OMB guidelines, the 7% discount rate is the principal discount rate for this evaluation.

Table 8-1. VTO R&D Investments in Energy Storage Technology, 1992–2012

Year	(1) VTO R&D Investments (2012$ thousands)	(2) VTO R&D Investments Discounted at 7% to 1/1/1992 (2012$ thousands)	(3) VTO R&D Investments Discounted at 3% to 1/1/1992 (2012$ thousands)
1992	39,783	39,783	39,783
1993	45,557	42,577	44,230
1994	51,699	45,156	48,731
1995	39,200	31,999	35,874
1996	37,145	28,338	33,003
1997	34,763	24,786	29,987
1998	37,397	24,919	31,319
1999	30,272	18,852	24,614
2000	30,474	17,736	24,056
2001	35,234	19,165	27,004
2002	33,375	16,966	24,834
2003	30,051	14,277	21,709
2004	26,987	11,983	18,928
2005	29,832	12,379	20,314
2006	31,444	12,195	20,788
2007	48,238	17,484	30,962
2008	52,128	17,658	32,484
2009	77,347	24,486	46,796
2010	82,035	24,271	48,187
2011	84,778	23,442	48,348
2012	93,034	24,042	51,511
Total	970,773	492,491	703,463

Note: The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Investment costs are assumed to have occurred at the beginning of each time period. Sums may not add to totals because of independent rounding. Undiscounted investment costs are presented in Appendix B.

8.2 ECONOMIC BENEFITS OF VTO'S R&D INVESTMENTS

Fuel cost savings in the amount of $3.3 billion were estimated through 2012. When these savings are discounted back to 1992, the present value is $952 million (Table 8-2).

At 7%, the midpoint of the range of economic value of environmental health benefits from Table 6-9 is $157 million, which is $46 million when discounted back to 1992. Only the

Table 8-2. Fuel Cost Savings Benefits, 1999–2012

Year	(1) Fuel Cost Savings (2012$ thousands)	(2) Fuel Cost Savings Discounted at 7% to 1/1/1992 (2012$ thousands)	(3) Fuel Cost Savings Discounted at 3% to 1/1/1992 (2012$ thousands)
1999	2	1	2
2000	1,611	876	1,235
2001	5,027	2,555	3,741
2002	10,773	5,118	7,783
2003	21,419	9,510	15,023
2004	43,500	18,051	29,621
2005	106,175	41,176	70,194
2006	187,326	67,896	120,237
2007	295,234	100,006	183,980
2008	423,230	133,984	256,061
2009	356,448	105,460	209,376
2010	461,639	127,647	263,266
2011	627,142	162,065	347,233
2012	736,723	177,928	396,025
Total	3,276,249	952,275	1,903,777

Note: Fuel cost savings are from Table 5-12. The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Economic benefits are assumed to be realized at the end of each time period. Sums may not add to totals because of independent rounding.

mean of the range of environmental health benefits, from Table 6-9, are included in Table 8-3 and used in the calculation of the performance measures.

8.3 ECONOMIC PERFORMANCE ANALYSIS

When monetized fuel savings and environmental health benefits are summed, at a 7% discount rate, benefits total $3,432 million and have a present value of $999 million (base year = 1992).

Three performance metrics were calculated using the data in Table 8-4: NPV, BCR, and IRR. Mathematically:

$$NPV = \left\{ \sum_{y=1999}^{2012} B_y (1+r)^{1992-(y+1)} \right\} - \left\{ \sum_{y=1992}^{2012} C_y (1+r)^{1992-y} \right\} \text{ and}$$

$$BCR = \left\{ \sum_{y=1999}^{2012} B_y (1+r)^{1992-(y+1)} \right\} \Big/ \left\{ \sum_{y=1992}^{2012} C_y (1+r)^{1992-y} \right\},$$

Table 8-3. Mean Environmental Health Benefits, 1999–2012

Year	(1) Environmental Health Benefits (2012$ thousands, applying a 7% discount rate in COBRA)	(2) Environmental Health Benefits (2012$ thousands, applying a 3% discount rate in COBRA)	(3) Environmental Health Benefits Discounted at 7% to 1/1/1992 (2012$ thousands)	(4) Environmental Health Benefits Discounted at 3% to 1/1/1992 (2012$ thousands)
1999	0	0	0	0
2000	121	136	66	104
2001	406	455	207	339
2002	944	1,058	448	764
2003	1,681	1,885	746	1,322
2004	3,027	3,394	1,256	2,311
2005	6,359	7,129	2,466	4,713
2006	9,860	11,054	3,574	7,095
2007	14,455	16,205	4,896	10,099
2008	18,072	20,260	5,721	12,258
2009	20,764	23,278	6,143	13,674
2010	23,351	26,179	6,457	14,930
2011	26,226	29,402	6,777	16,279
2012	31,468	35,279	7,600	18,964
Total	156,734	175,715	46,358	102,852

Note: The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Environmental health benefits are assumed to be realized at the end of each time period. Only the midpoints for these benefits from Table 6-9 are presented. Sums may not add to totals because of independent rounding.

where B_y is the value in 2012 dollars of the sum of economic benefits plus environmental health benefits realized in year y, C_y is the value in 2012 dollars of R&D investments made in year y, and r is the real interest rate.

Note that benefits are discounted an extra year, following the EERE guidelines (Ruegg & Jordan, 2011) that benefits for a given year are assumed to have been realized at year-end, while costs are assumed to have been incurred at year start. These formulas convert benefits and costs to January 1, 1992, present value.

The IRR is the real interest rate r^* for which the solution value of NPV = 0 and BCR = 1.

$$\left\{\sum_{y=1999}^{2012} B_y(1+r^*)^{1992-(y+1)}\right\} = \left\{\sum_{y=1992}^{2012} C_y(1+r^*)^{1992-y}\right\}.$$

Table 8-4. Total Benefits, 1999–2012

Year	(1) Total Benefits (2012$ thousands, applying a 7% discount rate in COBRA)	(2) Total Benefits (2012$ thousands, applying a 3% discount rate in COBRA)	(3) Total Benefits Discounted at 7% to 1/1/1992 (2012$ thousands)	(4) Total Benefits Discounted at 3% to 1/1/1992 (2012$ thousands)
1999	2	2	1	2
2000	1,732	1,747	942	1,339
2001	5,433	5,482	2,762	4,079
2002	11,717	11,831	5,567	8,547
2003	23,100	23,303	10,257	16,344
2004	46,527	46,894	19,307	31,932
2005	112,535	113,305	43,643	74,908
2006	197,186	198,380	71,469	127,333
2007	309,689	311,439	104,902	194,079
2008	441,302	443,491	139,705	268,319
2009	377,212	379,726	111,603	223,049
2010	484,990	487,818	134,104	278,196
2011	653,367	656,543	168,843	363,512
2012	768,191	772,002	185,528	414,989
Total	3,432,983	3,451,964	998,633	2,006,628

Note: The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Benefits are assumed to be realized at the end of each time period. Sums may not add to totals because of independent rounding.

In Table 8-5, the net present value, referenced to the base year of 1992, is $506 million. The BCRs is 2.03. The IRR is 14.3%.

The net economic benefits of VTO's investments in NiMH and Li-ion battery technologies have been socially valuable, even when the certain accrual of economic, energy, and environmental benefits for the remaining effectively useful life of EDVs on the road as of December 2012 are not taken into consideration.

8.4 SENSITIVITY ANALYSIS

The economic performance metrics reported in Table 8-5 were recalculated under two sensitivity analysis scenarios, both of which relate to the estimate of the increased market adoption of EDVs as presented in Table 5-6. Recall that these estimates were obtained from interview and survey responses to Questions 5 and 7. The calculated values in Table 5-6 are based

Table 8-5. Economic Performance Measures—Retrospective Analysis Period, 1992–2012

Measure	Discount Rate 7%	Discount Rate 3%	Internal Rate of Return
Net present value (base year =1992; millions of 2012$)	506	1,303	
Benefit-to-cost ratio	2.03	2.85	
Internal rate of return			14.3%

Note: The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. The internal rate of return was derived using the environmental health benefits reported in column (1) of Table 8-3, by discounting these values back to January 1, 1992. This results in a small overestimation of the IRR because the discount rate applied in COBRA is fixed at 7%. The overestimation is small: a rough overcorrection still gives an IRR greater than 14%.

In the lower bound sensitivity analysis scenario, the BCR is 1.73; VTO's investments in energy storage R&D have clearly been socially beneficial.

on an analysis of each respondent's assessment. To account for variability among respondents' assessments, a 90% confidence interval was constructed. The 90% confidence interval is plus/minus 1.65 standard deviations from the mean values in Table 5-6, which came from the data embedded in Figure 5-6.

- *Scenario 1 (Lower Bound).* Each year's estimate of the incremental increase in the market adoption of EDVs is reduced by 1.65 times its standard deviation. This sensitivity adjustment results in a lower-bound estimate of the market adoption below which the true value would be expected to occur only 5% of the time.
- *Scenario 2 (Upper Bound)*. Each year's estimate of the incremental increase in the market adoption of EDVs is increased by 1.65 times its standard deviation. This sensitivity adjustment results in an upper-bound estimate of the market adoption above which the true value would be expected to occur only 5% of the time.

In the lower bound scenario, the BCR is 1.73 (Table 8-6); clearly, VTO's investments in energy storage R&D have been socially beneficial. Additional analytical details about the sensitivity analysis are in Appendix F.

Table 8-6. Sensitivity Analysis for the Retrospective Case

Measure	Scenario 1 (Lower Bound)	Scenario 2 (Upper Bound)
Net present value (millions 2012$, 7% discount rate)	361	651
Benefit-to-cost ratio (7% discount rate)	1.73	2.32
Internal rate of return	12.8%	15.6%

9 Effective Useful Life Economic Performance Analysis, 1992–2022

This section calculates economic performance measures for fuel cost savings and environmental health benefits for 1992 through 2022. The continued operation of vehicles on the road as of December 31, 2012, is reasonably assured; therefore, the benefits expected to accrue over the remainder of these vehicles' effective useful lives are as well.

The more comprehensive measures presented in this section represent a more accurate view of the return on investment to date on VTO's investments in energy storage technologies through 2022.

Relevant to this useful life analysis are the same performance measures as in Section 8 except for the fact that the end period is 2022 rather than 2012. Mathematically:

$$PV = \left\{ \sum_{y=1999}^{2022} B_y (1+r)^{1992-(y+1)} \right\} - \left\{ \sum_{y=1992}^{2012} C_y (1+r)^{1992-y} \right\} \text{ and}$$

$$BCR = \left\{ \sum_{y=1999}^{2022} B_y (1+r)^{1992-(y+1)} \right\} \Big/ \left\{ \sum_{y=1992}^{2012} C_y (1+r)^{1992-y} \right\},$$

The IRR, $r*$, follows from:

$$\left\{ \sum_{y=1999}^{2022} B_y (1+r^*)^{1992-(y+1)} \right\} = \left\{ \sum_{y=1992}^{2012} C_y (1+r^*)^{1992-y} \right\}.$$

The relevant fuel cost savings and environmental health benefits, from 1999 through 2022, are in Tables 9-1 through 9-3.

Table 9-1. Fuel Cost Savings Benefits, 1999–2022 (2012$ thousands)

	(1) Fuel Cost Savings	(2) Fuel Cost Savings Discounted at 7% to 1/1/1992	(3) Fuel Cost Savings Discounted at 3% to 1/1/1992
1999	2	1	2
2000	1,611	876	1,235
2001	5,027	2,555	3,741
2002	10,773	5,118	7,783
2003	21,419	9,510	15,023
2004	43,500	18,051	29,621
2005	106,175	41,176	70,194
2006	187,326	67,896	120,237
2007	295,234	100,006	183,980
2008	423,230	133,984	256,061
2009	356,448	105,460	209,376
2010	461,639	127,647	263,266
2011	627,142	162,065	347,233
2012	736,723	177,928	396,025
2013	706,913	159,560	368,933
2014	668,594	141,038	338,771
2015	613,955	121,039	302,025
2016	539,246	99,356	257,547
2017	453,881	78,156	210,462
2018	355,171	57,158	159,894
2019	273,935	41,200	119,731
2020	203,423	28,594	86,322
2021	143,097	18,798	58,954
2022	73,768	9,057	29,506
1999–2012	3,276,249	952,275	1,903,777
1999–2022	7,308,232	1,706,230	3,835,922

Note: Fuel cost savings are from Table 5-12. The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Economic benefits are assumed to be realized at the end of each time period. Sums may not add to totals because of independent rounding.

Table 9-2. Mean Environmental Health Benefits, 1999–2022

Year	(1) Environmental Health Benefits (2012$ thousands, applying a 7% discount rate in COBRA)	(2) Environmental Health Benefits (2012$ thousands, applying a 3% discount rate in COBRA)	(3) Environmental Health Benefits Discounted at 7% to 1/1/1992 (2012$ thousands)	(4) Environmental Health Benefits Discounted at 3% to 1/1/1992 (2012$ thousands)
1999	0	0	0	0
2000	121	136	66	104
2001	406	455	207	339
2002	944	1,058	448	764
2003	1,681	1,885	746	1,322
2004	3,027	3,394	1,256	2,311
2005	6,359	7,129	2,466	4,713
2006	9,860	11,054	3,574	7,095
2007	14,455	16,205	4,896	10,099
2008	18,072	20,260	5,721	12,258
2009	20,764	23,278	6,143	13,674
2010	23,351	26,179	6,457	14,930
2011	26,226	29,402	6,777	16,279
2012	31,468	35,279	7,600	18,964
2013	30,539	34,237	6,893	17,868
2014	29,311	32,861	6,183	16,650
2015	27,279	30,583	5,378	15,045
2016	24,232	27,168	4,465	12,975
2017	20,912	23,445	3,601	10,871
2018	16,840	18,881	2,710	8,500
2019	13,422	15,049	2,019	6,577
2020	10,363	11,619	1,457	4,931
2021	7,624	8,548	1,002	3,522
2022	4,037	4,526	496	1,810
1999–2012	156,734	175,715	46,358	102,852
1999–2022	341,293	382,631	80,560	201,602

Note: Undiscounted totals are from Table 6-9. The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Economic benefits are assumed to be realized at the end of each time period. Sums may not add to totals because of independent rounding.

Table 9-3. Total Benefits, 1999–2022

Year	(1) Total Benefits (2012$ thousands, applying a 7% discount rate in COBRA)	(2) Total Benefits (2012$ thousands, applying a 3% discount rate in COBRA)	(3) Total Benefits Discounted at 7% to 1/1/1992 (2012$ thousands)	(4) Total Benefits Discounted at 3% to 1/1/1992 (2012$ thousands)
1999	2	2	1	2
2000	1,732	1,747	942	1,339
2001	5,433	5,482	2,762	4,079
2002	11,717	11,831	5,567	8,547
2003	23,100	23,303	10,257	16,344
2004	46,527	46,894	19,307	31,932
2005	112,535	113,305	43,643	74,908
2006	197,186	198,380	71,469	127,333
2007	309,689	311,439	104,902	194,079
2008	441,302	443,491	139,705	268,319
2009	377,212	379,726	111,603	223,049
2010	484,990	487,818	134,104	278,196
2011	653,367	656,543	168,843	363,512
2012	768,191	772,002	185,528	414,989
2013	737,452	741,151	166,453	386,801
2014	697,904	701,454	147,221	355,421
2015	641,234	644,538	126,417	317,070
2016	563,478	566,414	103,820	270,522
2017	474,793	477,327	81,757	221,334
2018	372,011	374,051	59,868	168,394
2019	287,358	288,984	43,219	126,308
2020	213,786	215,042	30,050	91,252
2021	150,720	151,644	19,800	62,475
2022	77,805	78,294	9,552	31,317
1999–2012	3,432,983	3,451,964	998,633	2,006,628
1999–2022	7,649,525	7,690,863	1,786,791	4,037,523

Note: The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. Economic benefits are assumed to be realized at the end of each time period. Sums may not add to totals because of independent rounding.

The effective useful life analysis, summarized in Table 9-4 accounts for the social benefits of vehicles purchased through 2012 that will remain on the road over their expected life.

Table 9-4. Economic Performance Measures—Effective Useful Life Analysis Period, 1992–2022

Measure	Discount Rate		Internal Rate of Return
	7%	3%	
Net present value (base year =1992; millions of 2012$)	1,294	3,334	
Benefit-to-cost ratio	3.63	5.74	
Internal rate of return			17.7%

Note: The 3% discount rate is presented for informational purposes only; the 7% rate is the principal discount rate for this evaluation. The internal rate of return was derived using the environmental health benefits reported in column (1) of Table 8-3, by discounting these values back to January 1, 1992. This results in a small overestimation of the IRR because the discount rate applied in COBRA is fixed at 7%. The overestimation is small: a rough overcorrection still gives an IRR greater than 14%.

When the useful life of a vehicle is considered, all the performance measures increase. NPV is $1.29 billion, the BCR is 3.63 (using a 7% discount rate), and the IRR is 17.7%.

The performance measures reported in Table 9-4 were recalculated under two sensitivity analysis scenarios, which relate to the market adoption of EDVs as presented in Table 5-6. Recall that these estimates were obtained from interview and survey responses to Questions 5 and 7. The calculated values in Table 5-6 are based on an analysis of each respondent's assessment. To account for variability among respondents' assessments, which are reflected in Figure 5-6, a 90% confidence interval was constructed; this interval is plus/minus 1.65 standard deviations from the values in Table 5-6, which came from the data embedded in Figure 5-6.

- *Scenario 1 (Lower Bound).* Each year's estimate of the incremental increase in the market adoption of EDVs is reduced by 1.65 times its standard deviation. This sensitivity adjustment results in a lower-bound estimate below which the true value would be expected to occur only 5% of the time.
- *Scenario 2 (Upper Bound)*. Each year's estimate of the incremental increase in the market adoption of EDVs is increased by 1.65 times its standard deviation. This sensitivity adjustment results in an upper-bound estimate above which the true value would be expected to occur only 5% of the time.

Even in the lower bound scenario, the BCR is 3.08 (Table 9-5); VTO's investment in energy storage R&D has clearly been socially beneficial. Additional analytical details about the sensitivity analysis are in Appendix F.

Table 9-5. Sensitivity Analysis for the Effective Useful Life Case

Measure	Scenario 1 (Lower Bound)	Scenario 2 (Upper Bound)
Net present value (millions 2012$, 7% discount rate)	1,025	1,564
Benefit-to-cost ratio (7% discount rate)	3.08	4.18
Internal rate of return	16.4%	18.8%

10 Summary Return on Investment and Conclusions

This benefit-cost evaluation shows that VTO's R&D investments in energy storage technologies for electric and hybrid cars and trucks have been socially valuable. Gross benefits from fuel savings were quantified first for EDVs on the road between 1999 and 2012 ($3.4 billion [2012$]), and second to account for these vehicles' remaining useful life from 1992 through 2022 ($7.6 billion) because these vehicles have an expected useful life of 11 years.

10.1 SUMMARY RETURN ON INVESTMENTS

When compared with VTO R&D investment costs of $971 million from 1992 through 2012 with the benefits that have accrued through 2012, the performance measures are

- NPV—$506 million, discounted at 7%;
- BCR—2.03-to-1, discounted at 7%; and
- IRR—14.3%.

When benefits are estimated through 2022, for those vehicles on the road as of December 2012, the performance measures increase to

- NPV—$1,294 million, discounted at 7%;
- BCR—3.63-to-1, discounted at 7%; and
- IRR—17.7%.

This second set of performance measures is more representative because the continued operation of EDVs on the road as of December 2012 through the end of their effective useful lives is reasonably certain.

The study also concluded the following result from VTO's support of NiMH and Li-ion R&D:

- Over the period from 1999 through 2012, in the absence of VTO support, the total number of hybrid cars and trucks on the road would be cut by almost half.
- Fuel savings amounted to 1.0 billion gallons of gasoline through 2012, and 2.1 billion gallons are expected to be saved through 2022 (for EDVs sold through the end of 2012).
- The fuel savings benefits from 1999 through 2012 totaled $3.3 billion in 2012 dollars, and from 1999 through 2022, they totaled $7.3 billion in 2012 dollars.
- The environmental health benefits from 1999 through 2012 totaled $157 million, and from 1999 through 2022, they totaled $341 million.

Table 10-1 summarizes calculations from preceding sections, presenting measures and metrics that report the return on VTO's investments in energy storage along economic, energy, environmental, energy security, and knowledge creation lines.

Table 10-1. Summary Benefit-Cost Evaluation Measures

	Benefits Period		
	Retrospective (1999–2012)	**Useful Life (1999–2022)**	**Unit of Measure**
Summary Performance Measures			
Total benefits	$3,433	$7,650	Million, 2012$
Total VTO investment costs through 2012	$971	$971	Million, 2012$
Net benefits	$2,462	$6,679	Million, 2012$
Net present value @ 7% [Base year = 1992]	$506	$1,294	Million, 2012$
Net present value @ 3% [Base year = 1992]	$1,303	$3,334	Million, 2012$
Benefit-to-cost ratio @ 7% real discount rate	2.03	3.63	
Benefit-to-cost ratio @ 3% real discount rate	2.85	5.74	
Internal rate of return (annual)	14.3%	17.7%	
Energy and Resource Benefits			
Fuel savings (gasoline)	1,029,784	2,125,539	Thousand gallons
Value of fuel savings	$3,276	$7,308	Million, 2012$

(continued)

Table 10-1. Summary Benefit-Cost Evaluation (continued)

	Benefits Period		
	Retrospective (1999–2012)	**Useful Life (1999–2022)**	**Unit of Measure**
Environmental Benefits[a]			
Avoided GHG emissions (CO_2eq)	6,989,237	14,461,042	Metric tons
Avoided volatile organic compounds emissions (VOCs)	3,928	7,926	Short tons
Avoided nitrogen oxides (NO_x)	1,217	2,324	Short tons
Avoided particulate matter emissions ($PM_{2.5}$)	2	16	Short tons
Avoided sulfur dioxide emissions (SO_2)	128	265	Short tons
Avoided ammonia emissions (NH_3)	643	1,329	Short tons
Avoided mortality[b]	20.04	42.39	Deaths
Avoided infant mortality[b]	0.02	0.05	Deaths
Avoided nonfatal heart attacks	6.96	14.73	Attacks
Avoided resp. hospital admissions.	4.34	9.17	Admissions
Avoided CDV hospital admissions	4.05	8.57	Admissions
Avoided acute bronchitis	18.24	38.57	Cases
Avoided upper respiratory symptoms	331.47	701.04	Episodes
Avoided lower respiratory symptoms	232.31	491.31	Episodes
Avoided asthma ER visits	7.79	16.48	Visits
Avoided MRAD	10,265.31	21,710.22	Incidences
Avoided work loss days	1,734.48	3,668.28	Days
Avoided asthma exacerbations	348.78	737.64	Episodes
Mean value of environmental health benefits @ 7%	$157	$341	Millions, 2012$
Mean value of environmental health benefits @ 3%	$176	$383	Millions, 2012$
Energy Security Benefits			
Avoided petroleum consumption	54,199,182	111,870,462	Barrels of oil
Avoided foreign petroleum consumption	27,226,445	47,833,782	Barrels of oil
Knowledge Benefits			
DOE-attributed patent families in energy storage	112	112	Patent families
DOE publications in batteries	2,337	2,337	Publications

[a] Environmental benefits were quantified using pump-to-wheels emissions factors.

[b] Researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Krewski et al. (2009) and Laden et al. (2006). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study. The average of the low and high estimates of health benefits produced by COBRA was used for this study.

10.2 CONSERVATIVE NATURE OF REPORTED RESULTS

This evaluation's results are conservative. Although we conclude that VTO did indeed have a significant impact on NiMH technology, the impact on Li-ion is greater. However, only 2 years of Li-ion powered vehicles are included in this analysis (2011 and 2012), and evaluation participants predict the availability of new models in multiple vehicle segments and increasing adoption of Li-ion–powered vehicles over the next 5 years.

The following analytical points and assumptions support our conclusion that results are conservative, and these should be considered when interpreting and communicating evaluation results:

- Benefits for NiMH and Li-ion battery technology alone are compared with costs of VTO's entire energy storage R&D investment portfolio. Benefits were not considered for other technologies supported by VTO.
- Only vehicles on the road before January 1, 2013, were included in the benefit-cost analysis; vehicles entering operation on or after this date will certainly contain technology support by VTO.
- VTO's return on investment in Li-ion is expected to be greater than VTO's return on investment in NiMH, yet only 2 years of market adoption of Li-ion–powered vehicles are included in the benefits estimation.
- Industry experts and funded companies participating in initial interviews and our main data collection generally noted that the counterfactual technology development assessments they provided were lower-bound estimates. This is particularly so because it was not possible for them to measure the extent to which EDV models could have been redesigned in the face of inferior battery technical performance characteristics. Not only would some vehicles not have been on the road, but those that would have been on the road would likely have been less efficient.
- Newer cars and trucks may in actuality have effective useful lives longer than the average of 11 years documented in federal statistics.
- EDVs' greater adoption in urban areas may have environmental benefits greater than what were estimated at the national level.

Based on the findings in this study, one should not generalize about the net benefits from EERE's R&D investments in other subprograms within VTO or within other energy areas.

11 References

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Appendix A: Overview of Vehicle Energy Storage Technology

This appendix describes the application of energy storage technology to power light-duty passenger vehicles and trucks on the road. It begins with a general overview of the technology and then describes NiMH and Li-ion battery technologies and electrochemical capacitors in Sections A.2, A.3, and A.4, respectively. The purpose of this section is to review key performance characteristics, technical challenges that motivated public-sector investment, and concepts and terms necessary to evaluate VTO's investments.

A.1 OVERVIEW OF ENERGY STORAGE TECHNOLOGY FOR ELECTRIC-DRIVE VEHICLES

Battery systems provide the power source for EDVs,[43] and the design of these systems determines the overall performance of an EDV in terms of

- how far it will travel (i.e., driving range),
- how quickly it will accelerate,
- how quickly it will be refilled (i.e., recharge rate), and
- how safe it will be in the event of an accident.

[43] The term *EDV* encompasses hybrids, plug-in hybrids, and all-electric vehicles.

The battery system used in a typical EDV is a complex engineering structure consisting of a number of assemblies and subassemblies. These assembly components can be divided into four main categories:

- battery (e.g., integrated battery cells or modules)
- electrical controls (e.g., power electronics, electronic control units, battery management systems, and inductors)
- safety systems (e.g., crash sensor and current sensor)
- maintenance facilities (e.g., blower and service plug)

The heart of an EDV battery system is a series of battery modules that are stacked in an array sized to meet the performance requirements of the EDV. Each module is composed of a series of battery cells and control electronics. If the battery system is the main energy source for vehicle propulsion, then it will be large and complex, and many battery modules (often 10 or more) will be needed to meet the performance requirements. In comparison, if the battery system is a supplement to another propulsion energy source (e.g., internal combustion engine), then the battery system will be significantly smaller (sometimes only one or two modules) and less complex than if the battery system were the main energy source. The number of cells in a module is determined by the performance specifications of the module.

Inside of each battery cell are three main components: an anode, a cathode, and an electrolyte. When a fully charged battery is connected to a motor or other electrical load, chemical energy stored in the battery causes a current to flow from the battery cathode through the external load and into the battery anode. The amount of energy that is delivered through this process is given by Joule’s law:

$$Energy = \frac{(Cell\ Voltage)^2}{(Cell\ Resistance)}\ x\ time$$

Because cell voltage and cell resistance are fundamental properties of the chemistry used in the battery cell, the choice of cell characteristics has an efficiency impact on the EDV battery system. In an ideal situation, the greatest amount of energy could be delivered if cell voltage was increased while simultaneously reducing cell resistance. Typically, however, it is not possible to achieve simultaneously both high cell voltage and low cell resistance. Thus, when designing a system, two cell options are available to use:

- Cells with water-based electrolytes, including cell chemistries such as NiMH. Such cells typically have low cell resistance but limited cell voltage (typically below 1.5 volts).
- Cells with electrolytes that are based on organic solvents (i.e., nonwater based) such as Li-ion. Such cells typically have high cell resistance and high cell voltages (typically greater the 3.0 volts), compared with cells with water-based electrolytes.

Cost also plays a role in the choice of battery chemistry; water-based battery cells are typically available at a lower cost than Li-ion cells.

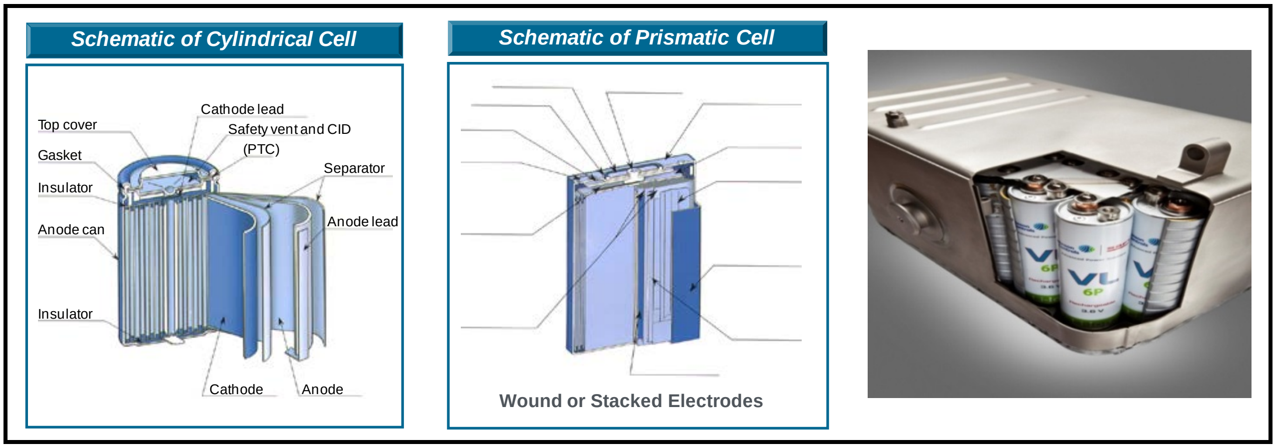
Battery cells used in consumer electronics can be made in large volumes using modern manufacturing methods. Comparable manufacturing methods are currently being developed for the larger EDV batteries.

Typically, battery cells are made either by winding electrodes into a cylinder that can be inserted into a round cell—this is called a jelly roll configuration because of its resemblance to the food—or by stacking alternating plates of the anode and cathode—this is called a prismatic configuration.[44] Schematic illustrations of both the cylindrical and prismatic forms are shown in the upper portion of Figure A-1.

Because propelling a vehicle requires a large amount of energy, a single battery cell is insufficient to supply the energy needs. Instead, many batteries are connected to form a battery module and, depending on the configuration of the EDV, battery modules are connected to form a battery pack.

[44] Cylindrical cells are made using the jelly roll process, whereas prismatic cells can be made using either the jelly roll or stacked plate structure.

Figure A-1. Schematic Illustration of Cylindrical and Prismatic Battery Cells and an Assembly of Cells into a Battery Module



Note: These modules are further assembled into the battery packs.

Source: Howell (2011).

The cells that form the core of the battery system comprise different cell chemistries, each with certain advantages and certain limitations. Table A-1 compares common cell chemistries. Lead acid batteries have been used for decades for starting, lighting, and ignition applications; and they offer high reliability at relatively low costs. However, lead acid batteries have a number of limitations, including very low energy density and a limited cycle life that precludes their viability for EDV applications. EDVs require more advanced battery technologies that can affordably achieve the power and energy density necessary to propel the vehicle for an extended range and that have the durability required to meet battery life requirements.

The remainder of this section focuses on two of these cell chemistries: NiMH and Li-ion battery technologies.

Table A-1. Technical Performance of Common Cell Chemistries Used in EDV Battery Pack Systems, circa 2010

Performance Characteristics	Lead Acid	Nickel Cadmium (NiCd)	Nickel Metal Hydride (NiMH)	Lithium Ion (Li-ion)
Electrolyte	Water based	Water based	Water based	Organic
Nominal cell voltage (V)	2.0	1.2	1.2	3.6
Energy density (Wh/kg)[a]	35	40–60	60	120
Power density (W/kg)[b]	180	150	250–1,000	1,800
Cycle life[c]	4,500	2,000	2,000	3,500
Cost ($/kWh)[d,e]	$269	$280	$500–$1,000	Consumer electronics: $300–$800 Vehicles: $1,000–$2,000e
Battery characteristics	High reliability, low cost	Memory effect	Currently, best value and most popular for hybrid electric vehicles (HEVs)	Small size, light weight

[a] Chargeable electrochemical energy per weight of battery pack.

[b] Proportion of dischargeable electric energy to charged energy.

[c] The number of charging/discharging cycles in battery's entire life.

[d] Calculated exchange rate is $1 = 92.99 yen (05/14/2010). Ranges given are approximate.

[e] Li-ion batteries for consumer electronics have lower costs than those for use in vehicles because of high-volume production and a mature market.

Source: Lowe, Tokuoka, Trigg, and Gereffi (2010, p. 13).

A.2 NIMH BATTERY TECHNOLOGY

NiMH batteries combine the chemistries of both nickel cadmium (NiCd)[45] and nickel hydrogen (NiH_2)[46] to deliver cells that have high energy storage densities (both gravimetric and volumetric), long cycle life, and low cost. The principal difference between NiCd and NiMH cells is the replacement of the cadmium electrode in NiCd cells with metal hydride material. This replacement reduces cell weight and has a significant benefit for cell capacity. Because NiCd and NiMH cells share the same positive electrodes, the materials and manufacturing breakthroughs that have been developed over the many years of NiCd cell manufacturing can be directly applied to NiMH cells. This interoperability undoubtedly sped the commercial introduction of NiMH cells because only the negative electrode needed to be developed.

The reactions occurring at the NiMH battery electrodes are as follows:

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[45] Prior to the introduction of NiMH batteries, NiCd was the leading secondary battery technology for hand-held devices because of its low cost. Cells based on NiCd chemistry have been commercially available for more than 60 years, and a number of materials and manufacturing breakthroughs have been developed during this span to increase cell capacity and cell lifetime and reduce cost. Among these breakthroughs are the sintered nickel electrode to increase capacity, porous current collectors to increase capacity, and high volume manufacturing technologies to reduce costs. The energy stored by unit of mass (aka, gravimetric energy density) of the current generation of NiCd cells is typically only 40 to 60 Watt hours per kilogram (Wh/kg), while the energy stored per unit volume (aka, volumetric energy density) is typically between 50 and 150 Watt hours per liter (Wh/L). Despite the advantages of the NiCd cell, two significant limitations of this chemistry are the energy density and the “memory effect.” The energy density of NiCd cells is limited by the weight of the materials used to construct the cell. If NiCd batteries are charged and discharged to the same level on a consistent basis, the cell develops a basis against operating outside this range, thus effectively reducing battery capacity. This is the basis of the “memory effect” that occurs with NiCd batteries.

[46] The NiH_2 battery is a high energy density secondary battery that is widely used in satellites and other aerospace applications. The battery consists of the nickel positive electrode, a platinum-impregnated carbon black negative electrode, and a potassium hydroxide electrolyte. Hydrogen is supplied to the cell in the form of gaseous hydrogen contained in a pressurized vessel containing the cell components. The key performance advantages of this battery are its high gravimetric energy density (75 Wh/kg) and its long cycle life (>20,000 cycles at 80% depth of discharge). However, the cost of this battery is relatively high so it is used in specialized applications such as aerospace.

$NiO(OH) + H_2O + e^- \leftrightarrow Ni(OH)_2 + OH^-$ at the nickel positive electrode (A.1)

and

$MH + OH^- \leftrightarrow H_2O + M + e^-$ at the metal hydride (M) negative electrode. (A.2)

This produces an overall cell reaction of

$$NiO(OH) + MH \leftrightarrow Ni(OH)_2 + + M. \quad (A.3)$$

The reactions occurring at the negative electrodes in NiH_2 and NiMH batteries are very similar, and the metal hydride negative electrode, M (metal) in equations (A.2) and (A.3), has been the object of intense development in industry between 1992 and 2003. The material in this electrode must act as a hydrogen sponge and store large amounts of H_2, but it must also have high electrical conductivity and be able to oxidize the hydrogen gas. Breakthroughs in intermetallic hydrogen storage compounds for a variety of applications (e.g., fuel cells and solid-state refrigeration) have been leveraged in developing this technology.

Two broad classes of materials are used for the negative electrodes in NiMH batteries. The most common negative electrode material is the AB_5 chemistry in which A represents a rare earth element (usually lanthanum) and B represents one or more transition metals (typically a mixture of nickel, cobalt, or manganese). Another metal hydride chemistry that has also received extensive attention is the AB_2 class of hydrogen storage materials, in which A is typically titanium and B is typically nickel. The AB_2 chemistry was the first chemistry tested in NiMH batteries and offers the highest available theoretical capacity.[47] However, despite substantial research, this class of materials exhibits unacceptably high fade characteristics during multiple charge/discharge cycles; thus, its commercial potential is limited at this time. Consequently, virtually all of the commercial NiMH batteries on the EDV market contain the AB_5 chemistry, which has a more stable capacity even after 1,000 charge-discharge cycles.

[47] Because of its potentially large theoretical capacity, Energy Conversion Devices (ECD) of Auburn Hills, Michigan, and its battery subsidiary, Ovonics, invested heavily in the AB_2 chemistry.

Charging of NiMH cells reverses the electrochemical reactions shown in equations (A.1) through (A.3) above. Typically, recharging of NiMH cells occurs at a constant voltage between 1.4 and 1.6 volts per cell (reversed polarity from the discharge reaction), which is close to the typical operating voltage of NiMH cells (1.2 volts). Each battery cell is given a rate capacity value at the factory determined by the amount of energy that the battery can hold when new. This value is usually expressed in units of mAhr, and the value will decline or fade during cell usage. When a battery is charged at sufficient currents to completely recharge in 1 hour, this recharge rate is termed 1C rate. Likewise, if the battery is charged at twice this current, it is being charged at a 2C rate, and charging a battery at 1/100 of that current is charging at a C/100 rate.

A typical charging algorithm for NiMH cells consists of some combination of fast charge at high currents for short periods of time (typically less than an hour or < 1C) and trickle charge at much lower currents for an extended period of time (e.g., C/100).[48] If the charging current is low enough, trickle charging can be performed indefinitely on NiMH cells producing cells that are completely charged when removed from the charger.

A critical component of charging NiMH cells is accurately determining when to terminate the cell charge. Failure to achieve proper fast charge cut-off can result in damage to the cell, including the possibility of an explosion. Among the most common charging termination methods for NiMH batteries are

- detecting the small cell voltage drop that occurs when the cell is fully charged and

[48] Charging a battery is analogous to filling a bucket with water. A large hose can be used to fill the bucket quickly, but the water flowing to the bucket must be turned off early to avoid spillage or other problems. In contrast, a smaller hose or even an eye dropper can be used to fill the bucket exactly to the desired level without any spillage. However, such procedures would significantly increase the time required to fill the bucket. For batteries, a large current can be applied at a negative voltage that is slightly above the discharge voltage (i.e., 1C rate or higher). However, this process, which is termed fast charging, will not fill the battery fully without causing some potential long-term problems. A slower charging procedure, termed trickle charging because a trickle of electrical current is used for charging, can charge cells very accurately, but takes a long time. Usually, a combination of fast charge and trickle charge is used in recharging batteries.

- detecting the small increase in cell temperature that occurs when the cell is fully charged.

Fast charging is usually performed using a smart charger that adjusts the charging voltage and current to maximize the energy stored in the battery. Most cell manufacturers recommend that trickle charging commence upon the termination of fast charge to ensure that the cell is fully charged.

When cells are connected together, care must be exercised in how they are charged because the impedance of each cell will be slightly different.[49] Charging cells in a module requires that higher voltages be supplied to the module to charge each cell to the desired 1.4 to 1.6 volts per cell. In addition, the charging current to each cell must be adjusted to achieve an equivalent level of charge. The state of charge of each cell is monitored, often using the temperature change method, and fast charging is terminated when a portion of the cells becomes fully charged.

A.3 LI-ION BATTERY TECHNOLOGY

The Li-ion battery chemistry is a relatively new rechargeable battery technology that was first commercialized in the early 1990s. The Li-ion battery consists of a lithium-containing negative electrode and a positive electrode that is typically made from a metal oxide or a metal phosphate. The lithium ions are shuttled between the positive and negative electrodes. At the beginning of the cell discharge, the lithium is located in the negative electrode. During cell discharge, lithium ions are transported by the electrolyte to the positive electrode and reversibly inserted. During recharging, the process is reversed and lithium ions are removed from the positive electrode and inserted into the negative electrode. The highly reversible nature of the Li-ion shuttling process imparts excellent cycling performance to the Li-ion battery.

There are several significant differences between Li-ion and NiMH batteries:

- Li-ion batteries operate on the electrochemical cycle of lithium, whereas NiMH batteries operate on the electrochemical cycle of hydrogen.

[49] This charging is analogous to simultaneously filling buckets of slighting different sizes and apertures from a single hose.

- Li-ion batteries use organic solvents to support the electrolytes, whereas NiMH batteries use water to support the electrolyte.
- Li-ion batteries operate at a higher voltage per cell (nominally 3.5 volts or higher) than NiMH batteries. As shown in equation (A.1) above, the higher cell voltage enables Li-ion batteries to store higher amounts of energy than is possible with lower cell voltages. The higher cell voltage is a result of using organic electrolytes that have higher voltage stability.
- The materials used in Li-ion batteries are intrinsically lighter than those of Ni-based batteries. For example, the density of carbon, a common Li-ion battery electrode, is 2.3 grams/cubic centimeter, whereas the density of nickel is nearly four times higher. This fact, combined with the higher cell operating voltage, produces higher energy storage densities per unit weight (i.e., gravimetric energy capacity) for Li-ion compared with NiMH cells.
- Because organic solvents are flammable, the combination of organic electrolytes and higher operational volts makes safety a greater concern for Li-ion batteries than for NiMH batteries.

Li-ion batteries and NiMH batteries have some similarities; both are available in cylindrical and prismatic form factors, and cylindrical cells are often made in a jellyroll configuration. As a result, battery packs containing Li-ion cells can often replace those containing NiMH cells provided that an adjustment is made for the differences in cell voltages and charging requirements. Typically, Li-ion cells require one-third of the number of cells as NiMH because the cell voltage is roughly three times higher for Li-ion cells.

Originally, rechargeable lithium batteries were made with a lithium metal electrode. Although a lithium metal electrode exhibits the highest possible energy storage density, this electrode exhibits poor cycle life under repeated charge/discharge cycles. To overcome this limitation, commercial rechargeable Li-ion battery cells use carbon as the host material for the lithium in the negative electrode. Carbon has the ability to function effectively as a lithium sponge, reversibly absorbing and releasing lithium ions in the intercalation process. The chemical reaction occurring at the negative electrode is

$$xLi^{+} + xe^{-} + 6C \leftrightarrow Li_xC_6. \qquad (A.4)$$

Extensive studies have been performed on carbon materials for use as the negative electrode in Li-ion battery cells. These carbon materials can be broadly divided into amorphous materials (i.e., having no long-range structure) and those formed into crystalline carbon forms such as graphite. Amorphous carbons, also called hard carbons, have the advantage of the highest theoretical capacities and the best stability in common Li-ion battery electrolytes. This material was used in the first commercial Li-ion battery cells sold by Sony in 1991. Unfortunately, the large surface area of hard carbons leads to a high irreversible capacity (i.e., large capacity loss on the first cycle) and rapid decrease in cell capacity. Alternatively, graphitic carbons exhibit low irreversible capacities and little capacity loss with cycling (i.e., fading) and have become the dominant negative electrode material in Li-ion battery cells. However, graphitic carbons have a lower stability in certain electrolytes (e.g., propylene carbonate), and the material may undergo exfoliation under certain conditions rendering the electrode useless. Alternatively, mixes of hard and graphitic carbons are sometimes used as either coatings (e.g., hard carbon coating over graphitic particles) or mixed phase materials containing both graphitic and amorphous phases (e.g., mesocarbon microbeads). Although hard carbons were used in the first Li-ion battery cells, they have generally fallen out of favor for high duty cycle applications such as portable electronics and EDVs. In these applications, negative electrodes with a high percentage of graphitic content are used. Examples of these types of materials include graphitized mesocarbons, hard carbon-coated natural graphites, and synthetic graphites. A comparison of the properties of hard carbon, graphitized mesocarbons, coated natural graphite, and synthetic graphite is shown in Table A-2.

Recently, attention has shifted to other potential Li-ion battery negative electrode materials such as silicon and metallic tin, both of which exhibit the potential to serve as host materials for lithium. These materials can achieve considerably higher reversible charge capacities than carbon-based materials. However, they both suffer from large dimensional changes during the lithium insertion and removal process, and these

Table A-2. Comparison of the Material Properties and Typical Electrochemical Charge Capacities of Select Commercial Carbon Materials for Negative Li-ion Battery Electrodes

Material Property	Hard-Carbon (Pitch Derived)	Graphitized Mesocarbon (MCMB-25-28)	Coated Natural Graphite	Synthetic Graphite (TIMREX SLG5)
Surface area (m^2/g)	4.3	1	1.5	1.5
Average particle size (μm)	9	25	18	22
Bulk density (g/cm^3)	0.35	0.90	0.83	0.60
Typical reversible charge capacity (mAh/g)	400	335	360	360

Source: Novak, Goers, and Spahr (2010, p. 276).

changes result in poor mechanical stability and limited cycle life for electrodes made from these materials. An alternative negative electrode formulation is a partial replacement of carbon for nanosized metals of tin, silicon, or other elements to form a hybrid electrode.[50] This approach offers the potential to deliver higher capacities while retaining some of the mechanical support of the carbon structure. In 2006, Sony introduced the first Li-ion battery cell containing a carbon-based hybrid material. Sony's Nexelion cell technology contains a graphite/cobalt-doped amorphous tin hybrid electrode, and the cell is targeted for use in low duty cycle applications such as video cameras.

Theoretically, lithium metal could also serve as the negative electrode in a lithium battery and deliver extremely high specific charge capacities of up to 3.9 Ahr/g. Lithium metal electrodes have performed exceptionally well in primary (i.e., nonrechargeable) cells. Unfortunately, the efficiency of a rechargeable lithium metal electrode is low, requiring an excess of lithium to achieve reasonable cycle life. In addition, lithium metal undergoes significant volumetric and morphological changes with continued cycling, and lithium metal is prone to form dendrites, which can short the two electrodes and produce an unsafe cell. For this reason, significant research is required before lithium metal electrodes displace carbon electrodes in rechargeable lithium batteries.

[50] See Novak, Goers, and Spahr (2010).

The positive electrode in a Li-ion battery cell is a metal oxide such as nickel oxide, cobalt oxide, or manganese oxide. These metal oxides also effectively function as lithium sponges and will absorb lithium during discharge and release it during recharge. The chemical reaction occurring at the cathode is illustrated in equation (A.5) for cobalt oxide:

$$LiCoO_2 \leftrightarrow Li_{1-x}CO + xLi^+ + xe^-. \qquad (A.5)$$

Materials chosen for use as the positive electrode in Li-ion batteries must be able to absorb and release large amounts of lithium ions and must be chemically and structurally stable during operation. In selecting appropriate materials, the battery designer must strike the proper balance between power, energy, safety, durability and lifetime, and cost. A list of common metal oxides used in Li-ion battery chemistries is provided in Table A-3. The most common chemistries are cobalt oxide (CoO_2) and nickel oxide (NiO_2) materials. Cobalt oxide is a relatively expensive material (i.e., poor cost performance), so combinations of CoO_2, NiO_2, and other metal oxides can often be used to improve cell cost without significantly affecting performance. Manganese oxide (MnO_2) and iron phosphate ($FePO_4$) are also commonly used because of their enhanced safety relative to the CoO_2 and NiO_2 materials. There is generally a trade-off between energy storage capacity and cathode safety, as shown in Table A-3. The materials with the highest capacity (e.g., CoO_2 and NiO_2) also can present a safety concern if the battery pack is compromised. In contrast, materials such as iron phosphate and manganese spinel have better safety performance than other materials, but they also typically have a lower capacity.

Safe charging of Li-ion battery cells requires tight controls on the charging process to prevent (1) lithium metal plating on the negative electrode and (2) excess voltage (i.e., overvoltage) conditions that can produce unsafe thermal runaway reactions in the cell. Most Li-ion battery cells are charged to 4.2 volts (+/− 0.050 volts), although the maximum charging voltage will vary depending on positive electrode chemistry. Higher charging voltages, within a narrow range, will increase capacity but at the expense of cell lifetime. Charging at a significantly higher voltage may produce an unstable cell that will fail catastrophically and in a potentially unsafe manner.

Table A-3. Illustrative Snapshot of Li-ion Chemistries with Automotive Applications, Circa 2008

Chemistry	Electrodes: Positive (Negative)	Companies	Automotive Status	Power	Energy	Safety	Life	Cost
Lithium cobalt oxide (LCO)	$LiCoO_2$ (Graphite)		Limited applications	+	+	–	–	–
Lithium nickel, cobalt, and aluminum (NCA)	$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ (Graphite)	JCI-Saft; GAIA; Matsuhita; Toyota	Pilot	+	+	+/–	+	+/–
Lithium iron phosphate (LFP)	$LiFePO_4$ (Graphite)	A123; Valence; GAIA	Pilot	+	+/–	+/–	+	+/–
Lithium nickel, manganese, and cobalt (NMC)	$Li(Ni_{0.33}Co_{0.33}Mn_{0.33})O_2$ (Graphite)	Litcel (Mitsubishi); Kokam; NEC Lamillion	Pilot	+/–	+/–	+/–	–	+/–
Lithium manganese spinel (LMS)	$LiMnO_2$ or $LiMn_2O_4$ ($Li_4Ti_5O_{12}$)	GS Yuasa; Litcel (Mitsubishi); NEC Lamillion; EnerDel	Development	+/–	–	+	+	+/–
Lithium titanium (LTO)	$LiMnO_2$ ($LiTiO_2$)	Altairnano; EnerDel	Development	–	–	+	+	–
Manganese nickel spinel (MNS)	$LiMn_{1.5}Ni_{0.5}O_4$ ($Li_4Ti_5O_{12}$)		Research	+	+/–	+	?	+/–
Manganese nickel (MN)	$Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$ (Graphite)		Research	+	+	+	?	+/–

Source: Axsen, Burke, and Kurani (2008, p. 19). Simple + or – is used to indicate generally favorable or unfavorable. More details are provided in the original source.

Typically, a Li-ion battery is charged in a two-step process: constant current followed by constant voltage. In the constant current portion of the charging cycling, a set current ranging from 0.5 to 0.8 of the rated charge capacity of the cell (i.e., 0.5C to 0.8C) is applied at an increasing voltage for approximately 1 hour. Then the cell is charged at a constant voltage (typically around 4.2 volts) with an exponentially decaying current until full charge is achieved.

A.4 ELECTROCHEMICAL CAPACITORS

Electrochemical capacitors, also known as ultracapacitors, are an advanced energy storage system that can provide exceptionally high power densities in a compact package. However, ultracapacitors only store a small amount of energy (often < 10% of the energy storage density of batteries), so they work best to meet short-duration, high-power demands. In vehicle propulsion, this capability is especially useful for accelerating, starting, or in other applications that require a short burst of energy. Ultracapacitors are often combined with Li-ion batteries because the cell resistance of Li-ion can limit their ability to meet the demand for large current variations with short duration.

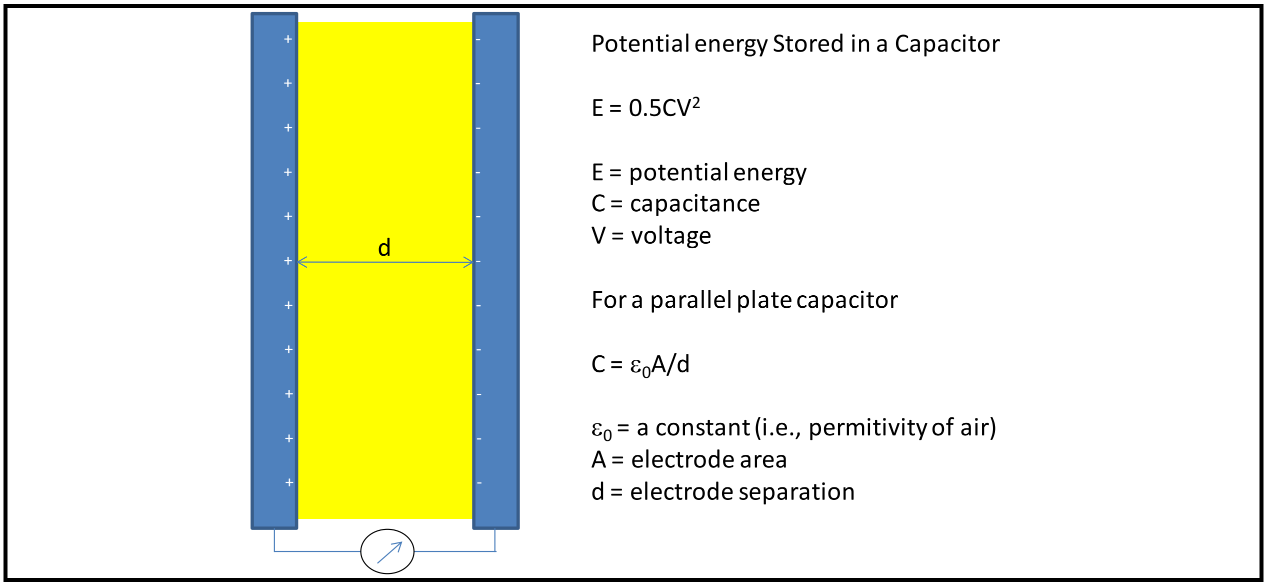
A significant difference between batteries and capacitors is their energy storage density and their power storage density. Batteries have high energy density, whereas ultracapacitors have high power density. Practically, this means that batteries can store the energy needed to propel a vehicle for extended distances, whereas capacitors can deliver the extra power (i.e., power is the energy delivered in short bursts) needed for climbing hills, accelerating, or starting a motor. The opposite is also true. Batteries can store large amounts when charged under constant conditions, whereas capacitors can store energy extremely quickly (e.g., capturing the energy dissipated during braking).

This high energy density of Li-ion batteries make them excellent candidates to provide long-term energy for an extended trip, while the high power density of ultracapacitors makes them excellent sources of energy in short bursts for rapid acceleration and hill climbing. Using an ultracapacitor in conjunction with a battery combines the power performance of the former with the greater energy storage capability of the latter. This can extend battery life, save on replacement and maintenance costs, and enable the battery size to be reduced. At the same time, such hybrid systems can increase the efficiency of the battery system by providing high peak power whenever necessary. Cell efficiency typically decreases when high current demand arises, so the use of an ultracapacitor to handle short high current demands will improve overall efficiency. Additional efficiency gains can be realized with the battery-ultracapacitor hybrid power system because the extremely rapid energy storage capability of ultracapacitors makes them ideal for recovering braking energy. The use of ultracapacitors for regenerative braking can greatly improve fuel efficiency under stop-and-go urban driving conditions. However, battery-ultracapacitor hybrids require additional power electronics (direct current/direct current or DC/DC), which may increase vehicle cost.

Although batteries and ultracapacitors are both electrochemical devices, the charge storage mechanism in an ultracapacitor is completely different from that of a battery. As discussed above, a battery stores chemical energy in the interior of the positive and negative electrodes, and the choice of battery chemistry plays a significant role in the amount of energy stored. However, capacitors, including ultracapacitors, store energy as electrostatic charges of opposite polarity on the surface of the electrodes. Because battery electrodes often undergo significant structural and morphological changes during charging and discharging as a result of materials absorbing and leaving the interior of the electrode, their lifetime typically is limited to less than 2,000 cycles. In contrast, capacitor electrodes may last for more than 100,000 charge-discharge cycles because the chemical changes are only occurring at the electrode surface, and virtually no chemical changes are occurring in the bulk electrode materials.

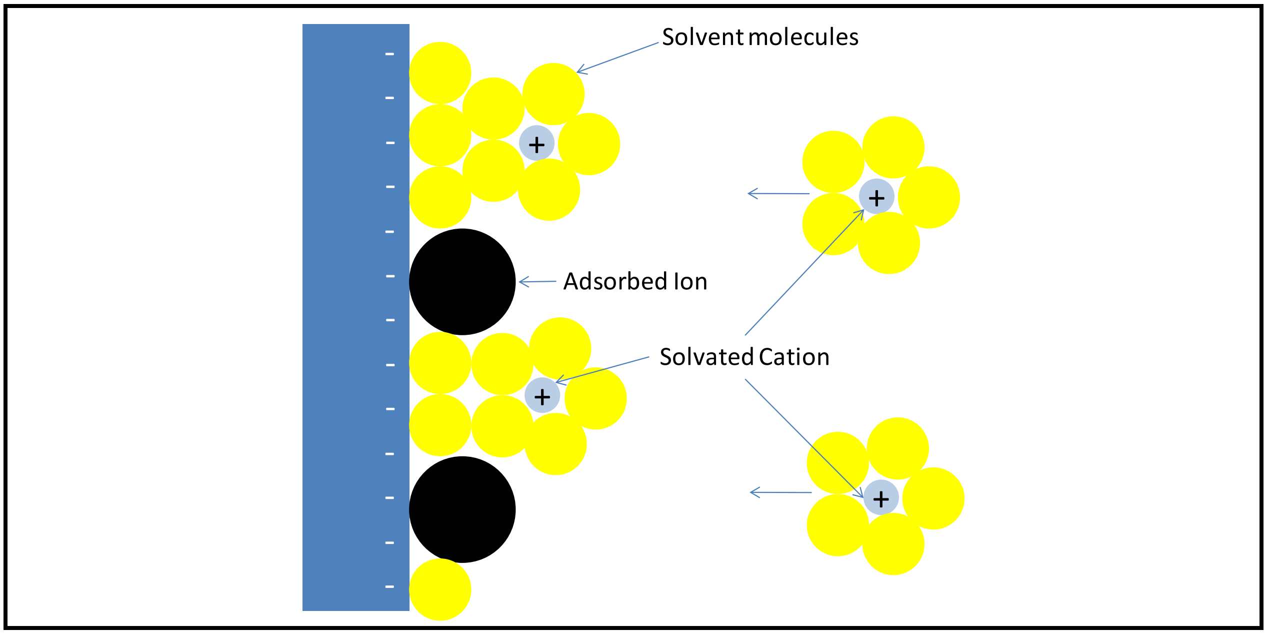
In a conventional capacitor used in electronic devices, the total energy stored increases with an increase in the amount of charge on the positive and negative electrodes, a reduction in the electrode separation, and as the electric potential between the electrodes is increased. This process is illustrated in Figure A-2. The material properties of the electrodes and the material separating the electrodes also play a significant role in the performance of a traditional capacitor, with a common limitation on performance being the interface between the electrode and electrolyte. Optimizing these geometric and material factors can increase the energy density for a given size of a traditional electrical capacitor. However, significantly larger capacitance values can be produced in ultracapacitors through the choice of materials that are capable of storing and separating electrostatic charges at the atomistic level, as shown in Figure A-3. Microporous and mesoporous electrodes create large surface areas that store surface charges quickly and can produce large capacitance values.

Figure A-2. Schematic Illustration of Energy Storage in a Traditional Capacitor



Note: The energy is stored as electrostatic charges on the surface of the electrodes. The separation between the charges determines the capacitance of the device, and the closer the charges, the higher the capacitance.

Figure A-3. Schematic Illustration of the Processes Used to Store Energy in an Ultracapacitor



Note: The ability of this device to separate opposite electrostatic charges over very short distances contributes to its high capacitance values.

Ultracapacitors store charge through two primary mechanisms: electrical double layer (EDL) capacitance and Faradaic pseudocapacitance. EDL capacitance arises from the separation of a charged electrode and solvated ions of opposite polarity. Faradaic pseudocapacitance is a highly reversible redox reaction typically occurring on the surface of an electrode.

Solvated ions, such as an aqueous salt solution, have larger sizes than the bare ion, but the total size of the solvated ion is typically less than a couple of nanometers (nm). To achieve high capacitance values, electrode materials with large surface areas are used. Typically, these materials are activated carbons mixed with a conductive agent, such as acetylene black and Ketjen black, and a binder such as Teflon or polyvinylidene fluoride.

Nanoscale materials with large surface areas, such as carbon nanotubes or graphene, have a large fraction of pores smaller than 2 nm (i.e., termed microporous) and give rise to large electrical double layer capacitances. In theory, such nanoscale materials can produce electrode capacitance values in excess of 200 Farads/gram. However, overreliance on microporous structures to build high charge densities can increase the charge/discharge time constant of a capacitor using such materials because of the restricted diffusion of solvated ions.

This situation is somewhat analogous to trying to fill an ocean using an eyedropper; it is achievable in theory but will take a long time. In contrast, mesoporous electrode structures, with pore diameters in the 2 nm to 50 nm range, have smaller surface areas than microporous materials but shorter charging/discharging time constants due to the more rapid diffusion of solvated ions. Thus, the ideal ultracapacitor material will balance the nanoscale structure of the electrode material by combining microporous and mesoporous features to achieve the high energy storage and fast charge/discharge kinetics.

Appendix B: VTO R&D Investments in Battery Energy Storage Technology, 1976–2012

Table B-1. VTO R&D Investments in Battery Energy Storage Technology, 1976–2012

Fiscal Year	(1) Nominal Appropriations (thousands)	(2) Price Index (2005 = 100)	(3) Price Index (2012 = 100)	(4) Appropriations (thousands of 2012$)
1976	5,300	35.5	30.8	17,209
1977	5,300	37.8	32.8	16,180
1978	5,500	40.4	35.1	15,690
1979	5,200	43.8	38.0	13,695
1980	7,700	47.8	41.4	18,580
1981	7,100	52.3	45.4	15,656
1982	5,300	55.5	48.1	11,015
1983	5,500	57.7	50.0	10,997
1984	4,400	59.9	51.9	8,479
1985	4,280	61.7	53.5	8,006
1986	3,622	63.1	54.7	6,628
1987	5,220	64.8	56.2	9,292
1988	5,174	67.0	58.1	8,904

(continued)

Table B-1. VTO R&D Investments in Battery Energy Storage Technology, 1976–2012 (continued)

Fiscal Year	(1) Nominal Appropriations (thousands)	(2) Price Index (2005 = 100)	(3) Price Index (2012 = 100)	(4) Appropriations (thousands of 2012$)
1989	6,417	69.6	60.3	10,641
1990	7,870	72.3	62.6	12,564
1991	8,836	74.8	64.9	13,625
1992	26,412	76.6	66.4	39,783
1993	30,911	78.3	67.9	45,557
1994	35,816	79.9	69.3	51,699
1995	27,724	81.6	70.7	39,200
1996	26,770	83.2	72.1	37,145
1997	25,497	84.6	73.3	34,763
1998	27,738	85.6	74.2	37,397
1999	22,784	86.8	75.3	30,272
2000	23,433	88.7	76.9	30,474
2001	27,706	90.7	78.6	35,234
2002	26,667	92.2	79.9	33,375
2003	24,517	94.1	81.6	30,051
2004	22,637	96.8	83.9	26,987
2005	25,855	100.0	86.7	29,832
2006	28,134	103.2	89.5	31,444
2007	44,412	106.2	92.1	48,238
2008	49,048	108.6	94.1	52,128
2009	73,425	109.5	94.9	77,347
2010	78,921	111.0	96.2	82,035
2011	83,299	113.4	98.3	84,778
2012	93,034	115.4	100.0	93,034

Notes: Nominal appropriations include battery storage R&D and Small Business Innovation Research funded R&D FY 1998 funding is an estimate of Phase 1 awards made in years prior to 1999. The estimate is based on Phase 2 awards between 1999 and 2003 for which no Phase 1 awards are tabulated. SBIR funding is the total funds awarded in a given year for automotive-related energy storage projects. The awards are made as a result of the solicitation and selection process managed by the Office of Science.

Sources: Appropriations data provided by DOE. GDP chain-type price index from U.S. Department of Commerce, Bureau of Economic Analysis, downloaded from the St. Louis Federal Reserve, http://research.stlouisfed.org/fred2/series/GDPCTPI/downloaddata?cid=21

Appendix C: HEV, PHEV, and EV Sales, by Model and Year

Table C-1. NiMH HEV Sales, by Model and Year

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Insight	17	3,788	4,726	2,216	1,168	583	666	722	3	—	20,572	20,962	15,549	5,846
Prius		5,562	15,556	20,119	24,627	53,991	107,897	106,971	181,221	158,886	139,682	140,928	136,463	223,905
Civic[a]				13,707	21,771	26,013	25,864	31,253	32,575	31,297	15,119	7,336	4,703	—
Accord[b]						653	16,826	5,598	3,405	198	1	—	—	—
Camry[c]								31,341	54,477	46,272	22,887	14,587	9,241	45,656
Lexus GS 450h[c]								1,784	1,645	678	469	305	282	607
Altima									8,388	8,819	9,357	6,710	3,236	103
Lexus LS 600h									937	980	258	129	84	54
Malibu										3,118	4,162	405	—	—
Aura										310	527	55	—	—
Fusion & Milan											17,022	22,232	11,286	14,100
Lexus HS 250h											6,699	10,663	2,864	649
Honda CR-z												5,249	11,330	4,192
Lincoln MKZ												1,192	5,739	6,067
Mercedes ML450												766	1	20
Mazda Tribute												655	484	90
Porsche Cayenne												206	1,571	1,180
Lexus CT 200h													14,381	17,671
VW Touareg													390	250
Porsche Panamera S													52	570
Ford C-Max														10,935

(continued)

Table C-1. NiMH HEV Sales, by Model and Year (continued)

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Lexus ES														7,041
Avalon														747
Escape/Mariner[c]						2,993	15,960	22,549	25,108	19,522	16,480	12,088	10,089	1,441
Highlander[c]							17,989	31,485	22,052	19,391	11,086	7,456	4,549	5,921
Lexus RX 450h[c]							20,674	20,161	17,291	15,200	14,464	15,119	10,723	12,223
Vue[d]									3,969	3,399	2,656	50	—	—
Tahoe, Yukon, Escalade										7,612	7,192	3,857	1,936	1,801
Aspen & Durango										81	42	—	—	—
Silverado & Sierra											1,598	2,393	1,165	940
Total	17	9,350	20,282	36,042	47,566	84,233	205,876	251,864	351,071	315,763	290,273	273,343	246,118	362,009

Note: Sales data were compiled from J.D. Power, EDTA, Hybrid Dashboard, and Green Car Congress. See: www.hybridcars.com. See specifically, for 2011 and 2012, http://www.hybridcars.com/december-2012-dashboard.

[a] The Civic hybrid sales are as reported by Honda through 2003 and 2004. Year 2005 and later data represent sales from EDTA, Hybrid Dashboard, and Green Car Congress.

[b] The Accord hybrid sales are from EDTA and Green Car Congress.

[c] The Escape, Highlander, RX 400h, Camry, and GS 450h hybrid sales represent registrations from EDTA through 2006. The 2007 sales of Escape and GS450h are from Green Car Congress.

[d] The 2007 Vue hybrid sales are from EDTA (Jan–May only) and later sales are from Hybrid Dashboard and Green Car Congress.

Table C-2. Li-ion HEV Sales, by Model and Year

	2010	2011	2012	Total
Mercedes S400	955	309	121	1,385
BMW ActiveHybrid	350	381	1,041	1,772
Hyundai Sonata		19,673	20,754	40,427
Buick Lacrosse		1,801	12,010	13,811
Kia Optima		403	10,084	10,487
Infinity M		378	691	1,069
Buick Regal		123	2,564	2,687
Malibu		24	16,664	16,688
Honda Civic			7,156	7,156
Acura ILX			972	972
Audi Q5			270	270
Volkswagen Jetta			162	162
Year total	1,305	23,092	72,489	96,886

Note: Sales data were compiled from J.D. Power, EDTA, Hybrid Dashboard, and Green Car Congress. See: www.hybridcars.com. See specifically, for 2011 and 2012, http://www.hybridcars.com/december-2012-dashboard.

Table C-3. PHEV/EV (Li-ion) Sales, by Model and Year

	2011	2012	Total
GM Volt[a]	7,671	23,461	31,132
Nissan Leaf	9,674	9,819	19,466
Smart ED	388	139	527
Mitsubishi i	80	588	668
Ford Focus	8	685	693
Toyota Prius PHV[a]		12,750	12,750
Tesla Model S		2,400	2,400
Ford C-Max Energi PHV[a]		2,374	2,374
BMW Active E		671	671
Toyota RAV4 EV		192	192
Honda Fit EV		93	93
Year total	17,821	53,172	70,993

Note: Sales data were compiled from J.D. Power, EDTA, Hybrid Dashboard, and Green Car Congress. See: http://www.hybridcars.com/december-2012-dashboard.

[a] Plug-in hybrids

Appendix D: Interview Guide

The U.S. Department of Energy's EERE contracted with RTI International to conduct a benefit-cost study of its VTO's R&D investments in NiMH and Li-ion battery technologies. Toward that end, we deeply appreciate your taking the time to share your insights with us through your answers to the following questions.

Your responses will be kept confidential; only consensus opinions, without attribution, will be included in our final report to EERE and VTO.

1. Please provide a brief description of your current battery research, including how (if at all) this research has been affected (directly or indirectly) by VTO investment in NiMH or Li-ion battery technologies.

2. Please provide a brief overview of any previous research related to NiMH or Li-ion battery technology. How (if at all) was this research affected (directly or indirectly) by VTO investment?

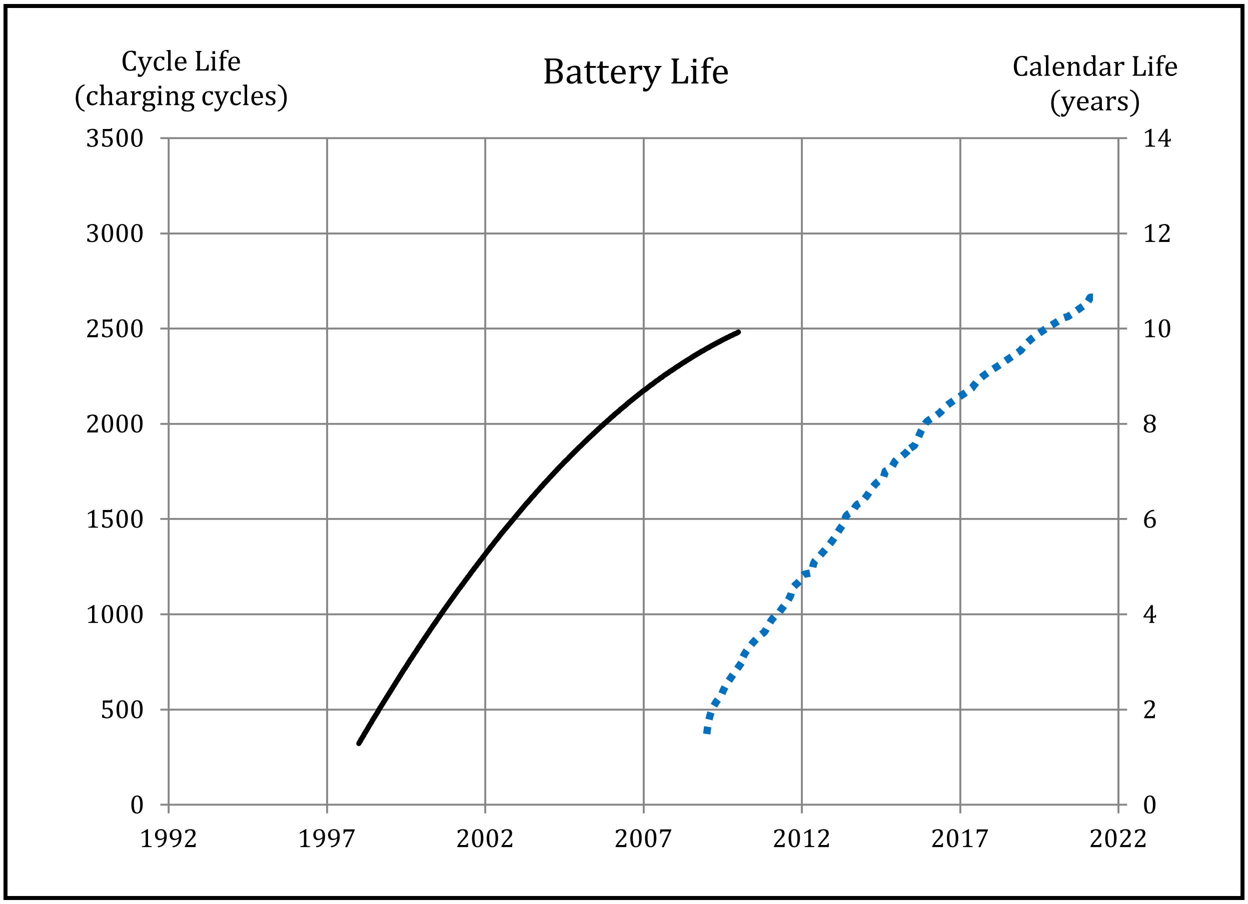
3. Shifting now to thinking about industry-wide battery research efforts, imagine a counterfactual scenario without VTO's support for NiMH and Li-ion battery technologies. Could you briefly describe how R&D performance, both in industry and in universities, might have been different?

4. The following three sets of graphs for battery life, energy density, and cost roughly describe how the state-of-the-art electric drive vehicle (EDV) battery technology has advanced over the past 15 years. Please indicate how you think the advancement of the state-of-the-art would have been different in the counterfactual scenario without VTO's support for NiMH and Li-ion battery technologies.

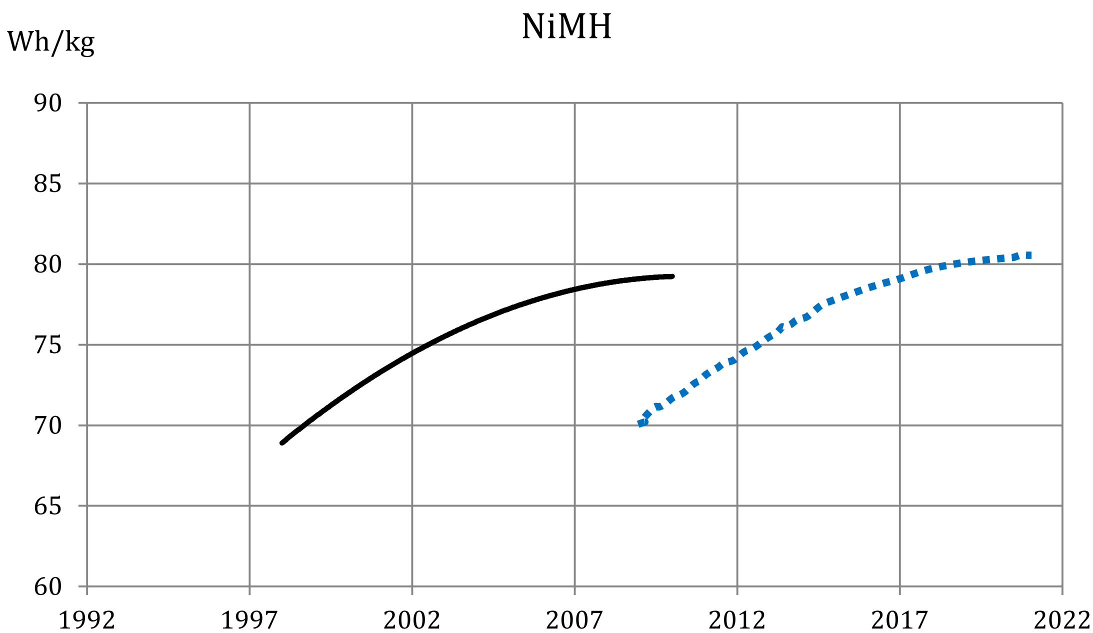
Please indicate how you think the graph would look in the counterfactual by clicking on the dotted line and dragging/resizing as appropriate.

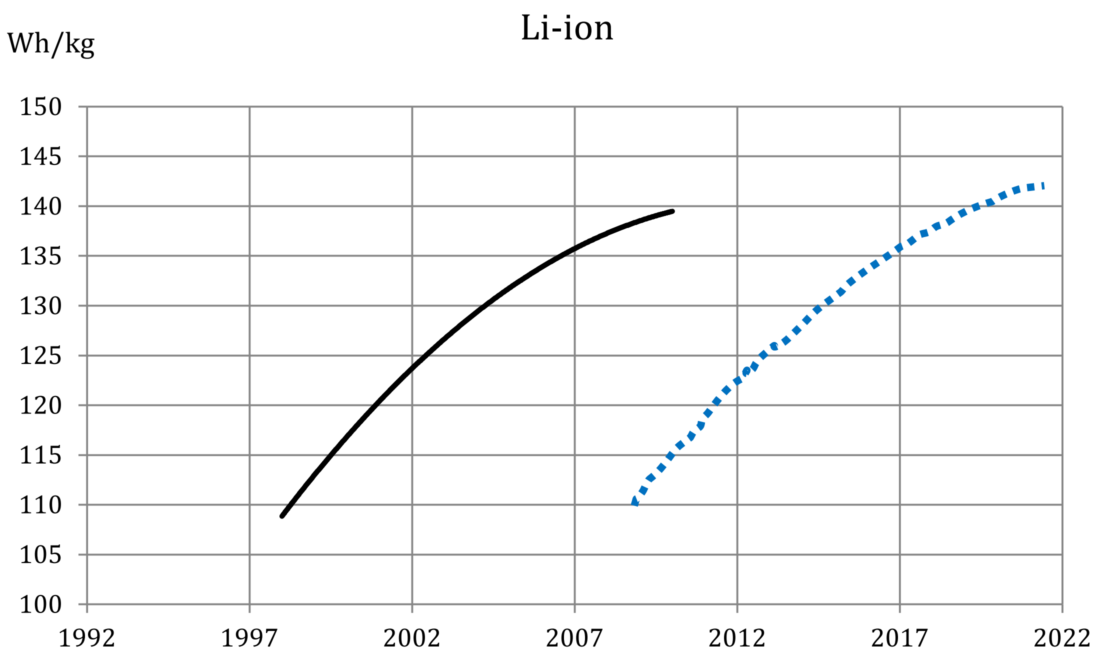
> *Note: At this level of abstraction, roughly describing the industry average state-of-the-art, we have shown one trend line for battery life, reflecting no significant difference between NiMH and Li-ion. If you wish to indicate different impacts on the different technologies, please copy the dotted line and indicate which technology each line represents.*

Charging Cycles and Calendar Life (assuming full discharge)

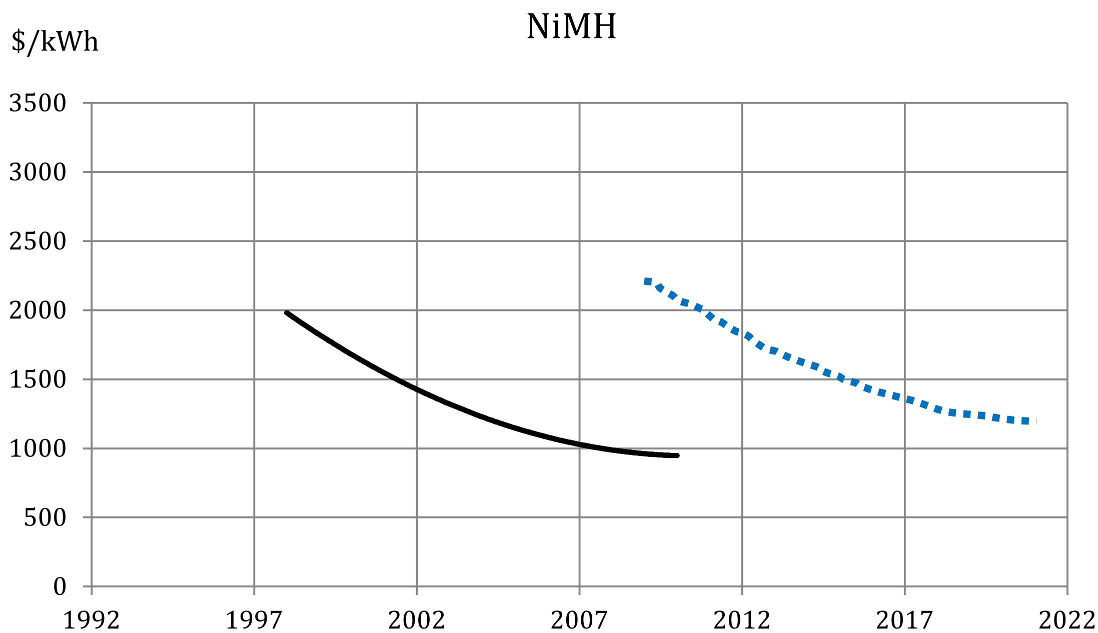


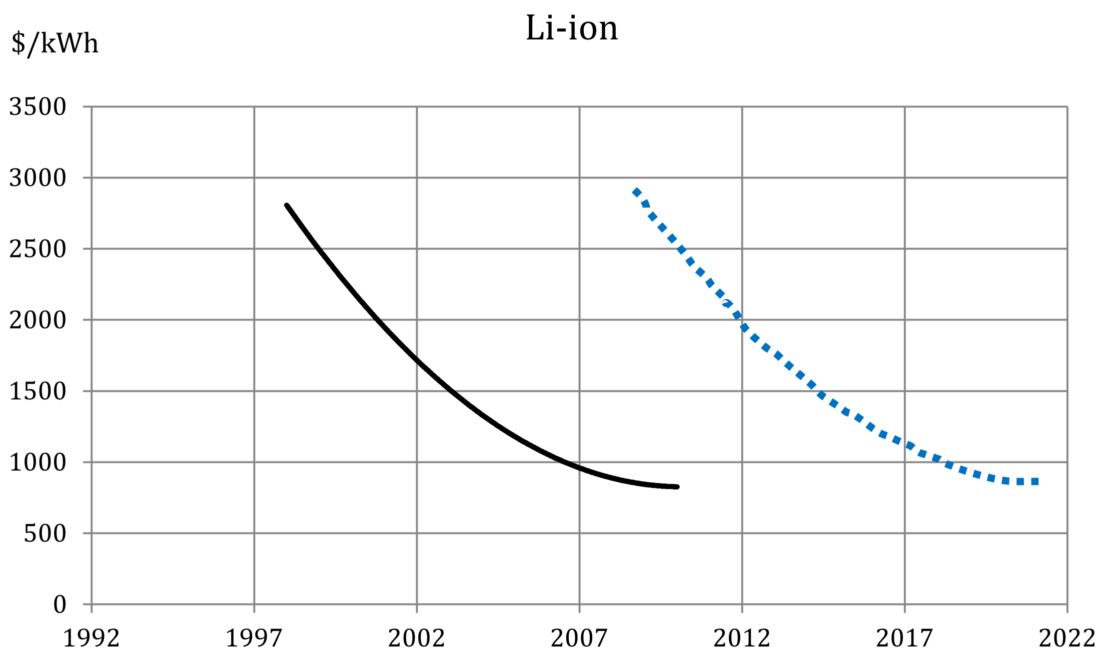
Energy Density (Wh/kg)





Cost ($/kWh)


NiMH
$/kWh
3500
3000
2500
2000
1500
1000
500
0
1992
1997
2002
2007
2012
2017
2022


Li-ion
$/kWh
3500
3000
2500
2000
1500
1000
500
0
1992
1997
2002
2007
2012
2017
2022

5. The following graph presents a stylized depiction of the adoption of both NiMH and Li-ion technologies in the U.S. market through the purchase of EDVs. Please indicate (by drawing on the graph or describing in words) how you think this adoption curve would have been different in the counterfactual scenario without VTO's support for NiMH and Li-ion battery technologies.

6. Li-ion technology made its way into the EDV market in a significant way relatively recently, making up roughly 4% of EDV sales in 2010 and 12% in 2011. In the counterfactual scenario without VTO's support for NiMH and Li-ion battery technologies, would the share of the EDV market represented by Li-ion have been different? If so, how?

7. For clarification, are the differences that you have described between the actual and counterfactual scenarios due ***entirely*** to VTO's financial support of NiMH and Li-ion technologies?

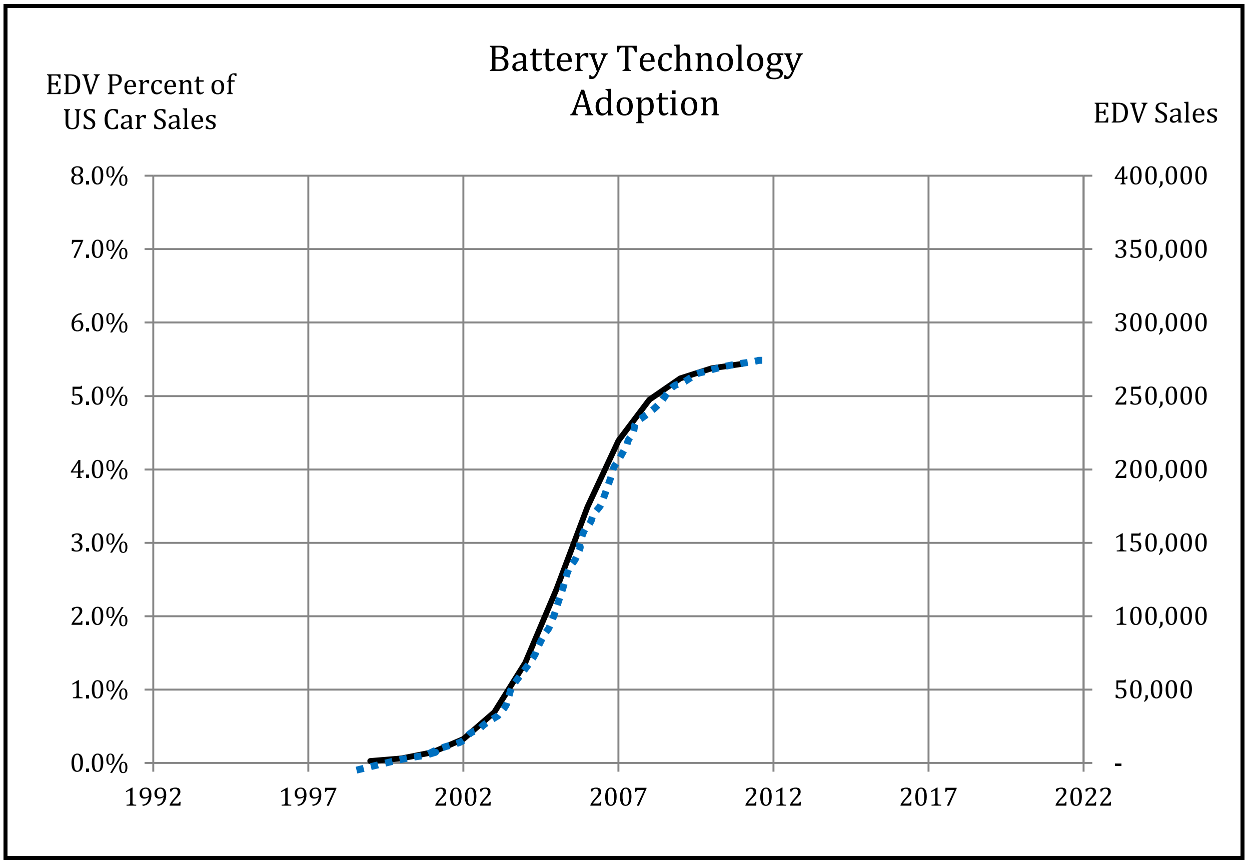


Table D-1. Participating Organizations in the Survey

Companies	Universities	National Laboratories
• A123 Systems (Navitas Systems) • Amprius • Applied Materials, Inc. • BASF Battery Materials, USA • BASF Catalysts, LLC • Dow Kokam, LLC • EnerDel, Inc. • FMC Corporation • Ford Motor Company • General Motors • H&T Waterbury • K2 Energy Solutions, Inc. • LG Chem Power, Inc. • Maxwell Technologies, Inc. • Miltec UV International • Nanosys, Inc. • Saft America, Inc. • Seeo, Inc. • Ultimate Membrane Technologies	• Northwestern University • Pennsylvania State University • SUNY Binghamton • University of Massachusetts Boston • University of Pittsburgh • University of Rhode Island	• Argonne National Laboratory • Brookhaven National Laboratory • Idaho National Laboratory • Lawrence Berkeley National Laboratory • National Renewable Energy Laboratory • Oak Ridge National Laboratory • Pacific Northwest National Laboratory • Southwest Research Institute • U.S. Army Research Laboratory

Note: Permission was given by those surveyed to list their affiliation.

Appendix E: Comparison of Company to Non-Company Responses

Table 5-6 and Figure 5-6 summarize the 44 responses to Question 5, where respondents were asked about counterfactual adoption of EDVs. These 44 responses included 18 from companies and 26 from university and national labs. The following analysis concludes that this would not be appropriate to consider company responses in isolation because the difference between the means of the 18 company and 26 noncompany responses is not statistically significant.

Table E-1 summarizes the 44 responses when the percentage of market adoption of EDVs resulting from VTO R&D investments is averaged over the 14 years from 1999 through 2012. To illustrate, using the means reported in Table 5-6 as an example, as if these numbers corresponded to a single respondent's shifting of the market adoption curve, the analysis that follows would treat those 14 observations as a single observation with a value of 44.5, which is calculated as follows for respondent i:

$$x_i = \frac{z_{1999}+z_{2000}+z_{2001}+\cdots+z_{2012}}{14} = \frac{40+44+47+\cdots+34}{14} = 44.5 \qquad \text{(E.1)}$$

This number is the percentage of EDV adoption that a respondent attributes to VTO R&D investments. A number closer to 100 credits more of the observed sales of EDVs to VTO, while a number closer to zero gives less credit to VTO.

Table E-1. Summary of the 44 Responses When the Percentage of Market Adoption of EDVs Resulting from VTO R&D Investments is Averaged Over the 14 Years from 1999 through 2012

Category of Organization	n	Mean ($\bar{x}$)[a]	Standard Deviation (s)[b]
Companies	18	41.6	22.9
Noncompanies	26	46.5	27.4
All responses	44	44.5	25.5

[a] The mean is calculated as follows: $\bar{x} = \sum_{i=1}^{n} x_i / n$.

[b] The standard deviation is calculated as follows: $s = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 / (n-1)}$.

E.1 THE TWO-SAMPLE *T* TEST

To test the hypothesis that the 18 company responses and the 26 noncompany responses are drawn from distributions with identical population means against the alternative hypothesis that the population means are different we performed a two-sample t test. That is, the question asked is: How likely is the observed difference in the sample means if the population means are equal? If it is sufficiently likely, we will conclude that it is appropriate to combine company and noncompany responses rather than treating each subsample separately.

The appropriate test statistic is

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad \text{(E.2)}$$

where s_p is the square root of the pooled variance:

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \quad \text{(E.3)}$$

In this case we have

$$t = \frac{46.5 - 41.6}{25.7 \sqrt{\frac{1}{18} + \frac{1}{26}}} = 0.6241 \quad \text{(E.4)}$$

with $n_1 + n_2 - 2 = 42$ degrees of freedom.

At the α level of significance, we would reject the null hypothesis that the population means are equal if $t = 0.6241$ is either less than $-t_{\alpha/2,42}$ or greater than $t_{\alpha/2,42}$. For example, consider a 20% chance of rejecting the null hypothesis when it is actually correct, that is, let $\alpha = 0.20$ and thus reject the null if t is either less than $-t_{0.1,42} = -0.8503$ or greater than $t_{0.1,42} = 0.8503$. Clearly the t statistic does not meet this threshold. In fact, $t_{0.2680,42} = 0.6241$, so, to reject the null hypothesis of equal means in this situation implies being wrong slightly more than 50% of the time. Put another way, the probability that the difference in means will be at least as large as what we have observed if all observations are drawn from the same distribution is 0.5359, large enough that the observed difference in sample means cannot be considered evidence of a difference in population means.

For this to be an exact test, the observations must be drawn from normal distributions with equal variances. Because these assumptions do not necessarily hold here, the results should be interpret with caution. Nevertheless, inferences based on this test are robust to small departures from these assumptions, and the test statistic did not even begin to approach the threshold of statistical significance. However, as an additional test, we used nonparametric bootstrap methods to confirm the result.

E.2 THE NONPARAMETRIC BOOTSTRAP

To test again the hypothesis that the 18 company responses and the 26 noncompany responses are drawn from distributions with identical population means against the alternative hypothesis that the population means are different, but in a way that does not require observations to be drawn from normal distributions with equal variances, the following analysis was performed.

The 44 observations were resampled with replacement to create simulated samples of 18 observations and 26 observations. The means were recalculated and it was noted whether their difference is greater (in absolute value) than 4.9 (the difference between 46.5 and 41.6). After doing this 1,000 times, the difference of the means for the two simulated samples was greater than 4.9 in 531 of the 1,000 simulations, very close to the 536 that would have been predicted by the two-sample *t* test.

Appendix F: Sensitivity Analysis

The evaluation metrics were recalculated under two alternative scenarios:

- ***Scenario 1 (Lower Bound).*** Each year's estimate of the incremental increase in EDVs was reduced by 1.65 times its standard deviation. This resulted in a lower-bound estimate below which the true value would be expected to occur only 5% of the time.
- ***Scenario 2 (Upper Bound)*—**Each year's estimate of the incremental increase in EDVs was increased by 1.65 times its standard deviation. This resulted in an upper-bound estimate above which the true value would be expected to occur only 5% of the time.

Evaluation metrics for the two scenarios are provided in Tables F-1 through F-4. Tables F-5 through F-8 provide year-by-year details for Scenarios 1 and 2.

Table F-1. Scenario 1 (Lower Bound) Evaluation Metrics—Effective Useful Life Analysis, 1992–2022

Metric	Discount Rate		Internal Rate of Return
	7%	3%	
Net present value (base year =1992; millions of 2012$)	1,025	2,719	
Benefit-to-cost ratio	3.08	4.87	
Internal rate of return			16.4%

Table F-2. Scenario 2 (Upper Bound) Evaluation Metrics—Effective Useful Life Analysis, 1992–2022

Metric	Discount Rate		Internal Rate of Return
	7%	3%	
Net present value (base year =1992; millions of 2012$)	1,564	3,949	
Benefit-to-cost ratio	4.18	6.61	
Internal rate of return			18.8%

Table F-3. Scenario 1 (Lower Bound) Evaluation Metrics—Retrospective Analysis, 1992–2012

Metric	Discount Rate		Internal Rate of Return
	7%	3%	
Net present value (base year =1992; millions of 2012$)	361	1,011	
Benefit-to-cost ratio	1.73	2.44	
Internal rate of return			12.8%

Table F-4. Scenario 2 (Upper Bound) Evaluation Metrics—Retrospective Analysis, 1992–2012

Metric	Discount Rate		Internal Rate of Return
	7%	3%	
Net present value (base year =1992; millions of 2012$)	651	1,595	
Benefit-to-cost ratio	2.32	3.27	
Internal rate of return			15.6%

Table F-5. Scenario 1 (Lower Bound) Economic Benefits (thousands 2012$)

	Thousands of 2012$		
Year	**(1) Fuel Savings**	**(2) Fuel Savings Discounted at 7% to 1/1/1992**	**(3) Fuel Savings Discounted at 3% to 1/1/1992**
1999	2	1	1
2000	1,315	715	1,008
2001	4,190	2,130	3,118
2002	9,102	4,324	6,575
2003	18,235	8,097	12,790
2004	37,236	15,452	25,356
2005	91,225	35,378	60,310
2006	161,124	58,399	103,419
2007	253,921	86,012	158,235
2008	363,644	115,120	220,010
2009	305,698	90,445	179,565
2010	394,853	109,180	225,179
2011	534,423	138,105	295,897
2012	623,538	150,593	335,183
2013	598,128	135,005	312,159
2014	565,583	119,308	286,576
2015	519,029	102,325	255,328
2016	454,891	83,813	217,258
2017	381,586	65,707	176,939
2018	297,032	47,801	133,720
2019	227,728	34,251	99,535
2020	168,101	23,629	71,333
2021	117,600	15,449	48,450
2022	60,378	7,413	24,150
1999–2012		813,951	1,626,647
1999–2022		1,448,652	3,252,096

Note: Economic benefits are assumed to be realized at the end of each time period.

Table F-6. Scenario 1 (Lower Bound) Environmental Health Benefits (thousands 2012$)

Year	(1) Environmental Health Benefits (thousands of 2012$, applying a 7% discount rate in COBRA)	(2) Environmental Health Benefits (thousands of 2012$, applying a 3% discount rate in COBRA)	(3) Environmental Health Benefits Discounted at 7% to 1/1/1992 (thousands of 2012$)	(4) Environmental Health Benefits Discounted at 3% to 1/1/1992 (thousands of 2012$)
1999	0	0	0	0
2000	99	110	54	85
2001	338	379	172	282
2002	797	894	379	646
2003	1,431	1,605	636	1,125
2004	2,591	2,905	1,075	1,978
2005	5,464	6,126	2,119	4,050
2006	8,480	9,507	3,074	6,102
2007	12,431	13,937	4,211	8,685
2008	15,528	17,408	4,916	10,532
2009	17,809	19,965	5,269	11,728
2010	19,976	22,395	5,524	12,772
2011	22,346	25,052	5,775	13,871
2012	26,614	29,837	6,428	16,039
2013	25,819	28,946	5,828	15,107
2014	24,774	27,775	5,226	14,073
2015	23,040	25,830	4,542	12,707
2016	20,417	22,890	3,762	10,933
2017	17,560	19,687	3,024	9,129
2018	14,068	15,772	2,264	7,101
2019	11,148	12,499	1,677	5,463
2020	8,559	9,596	1,203	4,072
2021	6,265	7,024	823	2,894
2022	3,303	3,704	406	1,481
1999–2012			39,629	87,894
1999–2022			68,383	170,853

Note: Environmental health benefits are assumed to be realized at the end of each time period.

Table F-7. Scenario 2 (Upper Bound) Economic Benefits (thousands 2012$)

	(1) Fuel Savings	(2) Fuel Savings Discounted at 7% to 1/1/1992	(3) Fuel Savings Discounted at 3% to 1/1/1992
1999	3	2	2
2000	1,908	1,038	1,462
2001	5,864	2,981	4,363
2002	12,444	5,912	8,990
2003	24,602	10,924	17,255
2004	49,764	20,650	33,887
2005	121,126	46,975	80,079
2006	213,528	77,393	137,056
2007	336,547	114,000	209,725
2008	482,817	152,848	292,112
2009	407,197	120,475	239,185
2010	528,424	146,114	301,353
2011	719,860	186,026	398,569
2012	849,907	205,264	456,867
2013	815,699	184,114	425,707
2014	771,604	162,767	390,965
2015	708,881	139,753	348,722
2016	623,601	114,898	297,836
2017	526,177	90,605	243,986
2018	413,310	66,514	186,068
2019	320,142	48,150	139,927
2020	238,744	33,559	101,310
2021	168,593	22,148	69,458
2022	87,158	10,701	34,862
2013–2022		1,090,599	2,180,907
1999–2022		1,963,809	4,419,747

Note: Economic benefits are assumed to be realized at the end of each time period.

Table F-8. Scenario 2 (Upper Bound) Environmental Health Benefits (thousands 2012$)

Year	(1) Environmental Health Benefits (thousands of 2012$, applying a 7% discount rate in COBRA)	(2) Environmental Health Benefits (thousands of 2012$, applying a 3% discount rate in COBRA)	(3) Environmental Health Benefits Discounted at 7% to 1/1/1992 (thousands of 2012$)	(4) Environmental Health Benefits Discounted at 3% to 1/1/1992 (thousands of 2012$)
1999	0	0	0	0
2000	143	160	78	123
2001	474	531	241	395
2002	1,090	1,222	518	883
2003	1,931	2,165	857	1,518
2004	3,463	3,882	1,437	2,644
2005	7,255	8,133	2,814	5,377
2006	11,240	12,601	4,074	8,088
2007	16,478	18,474	5,582	11,512
2008	20,616	23,113	6,527	13,984
2009	23,719	26,592	7,018	15,620
2010	26,727	29,963	7,390	17,088
2011	30,106	33,752	7,780	18,688
2012	36,322	40,720	8,772	21,889
2013	35,258	39,528	7,958	20,630
2014	33,847	37,947	7,140	19,227
2015	31,518	35,336	6,214	17,383
2016	28,047	31,445	5,168	15,018
2017	24,263	27,203	4,178	12,614
2018	19,613	21,989	3,156	9,899
2019	15,697	17,599	2,361	7,692
2020	12,168	13,642	1,710	5,789
2021	8,983	10,071	1,180	4,149
2022	4,769	5,347	586	2,139
1999–2012			53,087	117,809
1999–2022			92,737	232,349

Note: Environmental health benefits are assumed to be realized at the end of each time period.

Appendix G: Well-to-Wheels Emissions Analysis

In this appendix, an assessment of the WtW, or total, avoided emissions is provided as well as an overview of the COBRA model.

G.1 WTW AVOIDED EMISSIONS

The WtW analysis accounts for emissions from feedstock and the distribution of fuel (WtP) in addition to those emissions from operating the vehicle (PtW). Although the emissions factors are different for the WtW analysis, avoided emissions were calculated in the same manner as the PtW analysis in Section 6.

Table G-1. WtW GHG Emissions Factors (g/mile)

	GV	HEV	PHEV	EV
Models 1999–2005				
CO_2eq	453.1	322.9		
Models 2006–2012				
CO_2eq	425.2	303.1	333.8	283.6

Source: ANL (2012).

Figure G-1. WtW Avoided GHG Emissions (thousands of metric tons of CO_2eq)

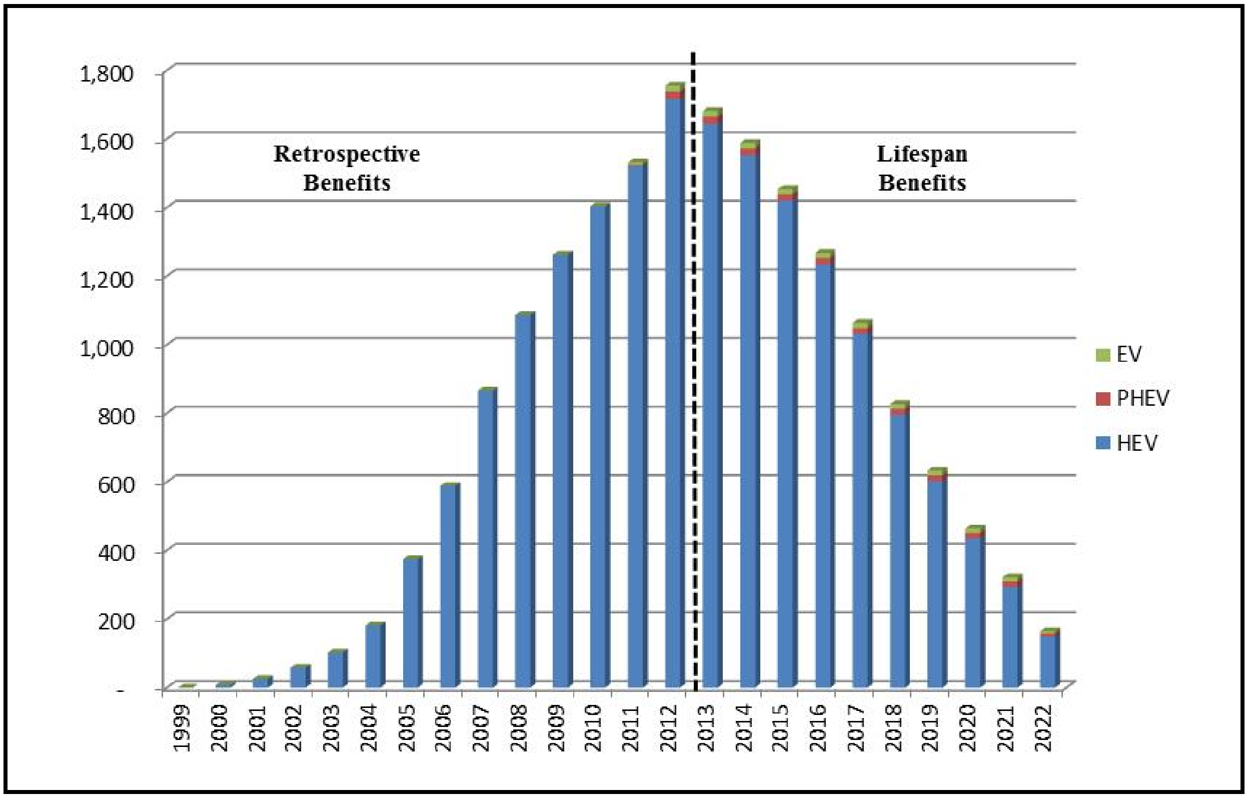


Table G-2. WtW Avoided GHG Emissions by Vehicle Type (thousands of metric tons of CO_2eq)

Vehicle Type	Retrospective	Life Cycle
HEV	9,198	18,358
PHEV	24	193
EV	25	163
Total	9,247	18,714

Table G-3. WtW Emissions Factors (mg/mile)

	(1) ICV	(2) HEV	(3) PHEV	(4) EV
Models 1999–2005				
VOC [a]	265.0	168.0	—	—
NO_x	389.5	295.9	—	—
$PM_{2.5}$	29.4	23.1	—	—
VOC_{evap}	58.0	58.0	—	—
SO_2 [b]	147.2	105.2	—	—
NH_3 [c]	36.9	23.4	—	—
Models 2006–2012				
VOC	228.9	147.0	112.9	23.4
NO_x	273.5	204.0	190.4	111.6
$PM_{2.5}$	26.9	21.3	62.6	119.2
VOC_{evap}	57.0	57.0	34.6	0.0
SO_2	126.8	90.6	355.8	719.8
NH_3	41.0	26.3	20.2	4.2

[a] VOC emissions were derived from two sources: the emissions from vehicle exhaust and from the evaporation of gasoline in the fuel system (U.S. EPA, 2000). These emissions are listed separately in this table and then are combined for an estimate of total avoided VOC emissions in subsequent tables.

[b] Emissions factors for SO_x were used as a proxy for SO_2 as for most combustion processes in GREET. SO_x is nearly 100% of SO_2.

[c] NH_3 WtW emissions for GV were scaled based on the percentage increase of VOC emissions from PtW to WtW. EDV reductions in NH_3 were scaled based on the percentage reduction of VOCs.

Source: ANL (2012) and EPA (2013).

Table G-4. WtW Avoided Emissions (short tons)

Year	(1) VOC	(2) NO_x	(3) $PM_{2.5}$	(4) SO_2	(5) NH_3
1999	0	0	0	0	0
2000	6	6	0	3	1
2001	21	20	1	9	3
2002	48	46	3	21	7
2003	84	81	5	37	12
2004	149	144	10	65	21
2005	308	297	20	133	43
2006	465	430	30	203	71
2007	670	602	44	294	108
2008	832	737	55	365	138
2009	961	846	64	423	161
2010	1,065	933	71	468	180
2011	1,171	1,016	70	463	199
2012	1,364	1,166	65	433	233
2013	1,306	1,113	62	409	223
2014	1,231	1,047	58	384	212
2015	1,122	947	52	346	195
2016	975	811	43	285	172
2017	823	683	33	221	145
2018	647	534	22	147	114
2019	502	412	13	87	88
2020	376	306	5	36	65
2021	268	215	0	−1	46
2022	139	111	−1	−5	24
Retrospective analysis (1999–2012)	7,145	6,325	440	2,916	1,177
Useful life analysis (1999–2022)	14,533	12,504	728	4,824	2,462

Table G-5. WtW Avoided Emissions, by Vehicle Type (short tons)

	(1) VOC	(2) NO_x	(3) $PM_{2.5}$	(4) SO_2	(5) NH_3
Retrospective Analysis (1999–2012)					
HEV	7,054	6,269	469	3,097	1,164
PHEV	40	24	−10	−67	6
EV	50	31	−18	−114	7
Total	7,145	6,325	440	2,916	1,177
Life-Cycle Analysis (1999–2022)					
HEV	13,878	12,105	928	6,109	2,367
PHEV	323	194	−83	−534	48
EV	332	205	−117	−750	47
Total	14,533	12,504	728	4,824	2,462

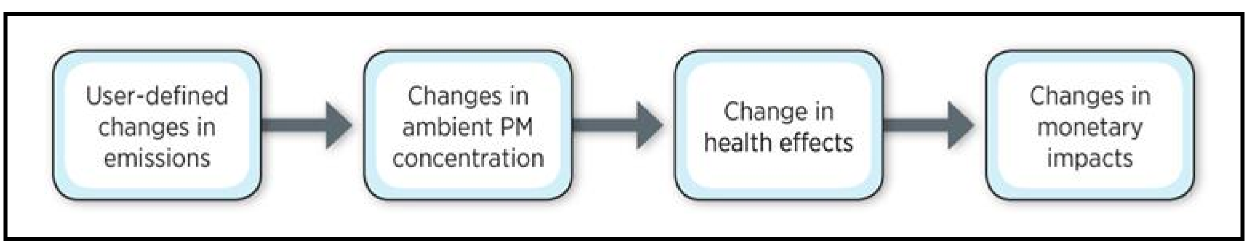
Note: Values may not add because of rounding.

G.2 SUMMARY OF THE COBRA MODEL

The COBRA model provides estimates of health effect impacts and the economic value of these impacts resulting from emission changes. The COBRA model was developed by the U.S. EPA to be used as a screening tool that enables users to obtain a first-order approximation of benefits due to different air pollution mitigation policies.

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in PM concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays (O'Connor et al., 2013). Figure G-2 provides an overview of the modeling steps.

Figure G-2. COBRA Model Overview



Source: U.S. EPA (2012d).

G.2.1 Changes in Emission → Changes in Ambient PM Concentrations

The user provides changes (decreases) in emissions of pollutants ($PM_{2.5}$, SO_2, NO_x, VOCs, NH_3) and identifies the economic sector from which the emissions are being reduced. These changes are in total short tons of pollutants by sector for the U.S. economy for the chosen analysis year. The economic sectors chosen determine the underlying spatial distribution of emissions and hence the characteristics of the human population that is affected. [51] For example, emissions reductions due to the use of EDVs are typically applied to light-duty gasoline vehicles.

The S-R matrix consists of fixed transfer coefficients that reflect the relationship between annual average $PM_{2.5}$ concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by $PM_{2.5}$ species to this concentration from each emission source. This matrix provides quick but rough estimates of the impact of emission changes on ambient $PM_{2.5}$ levels as compared with the detailed estimates provided by more sophisticated air quality models (U.S. EPA, 2012d).

G.2.2 Changes in Ambient PM Concentrations → Changes in Health Effects

The model then translates the changes in ambient PM concentration to changes in incidence of human health effects using a range of health impact functions and estimated baseline incidence rates for each health endpoint. The data used to estimate baseline incidence rates and the health impact functions used vary across the different health endpoints. To be consistent with prior U.S. EPA analyses, the health impact functions and the unit economic value used in COBRA are the same as the ones used for the Mercury and Air Toxics Standards (MATS) Final Rule (U.S. EPA, 2012d). The U.S. population estimates are based on projections from Woods & Poole (2011).

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[51] The COBRA model has a variety of spatial capabilities. However, for this study there was limited information on the specific location of pollution reductions. Thus, a national analysis was conducted where the national distribution of emissions was used to determine the emission location as input to the S-R matrix.

The model provides (in the form of a table or map) changes in the number of cases for each health effect between the baseline emissions scenario (included in the model) and the analysis scenario. The different health endpoints are included in Table G-6.

Each health effect is described briefly below. For additional detail on the epidemiological studies, functional forms, and coefficients used in COBRA, see Appendix C of the COBRA user's manual (U.S. EPA, 2012d).

Mortality researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Krewski et al. (2009) and by a Six-City cohort by Laden et al. (2006). These two studies

Table G-6. Health Endpoints Included in COBRA

Health Effect	Description
Mortality	Number of deaths (adult or infant)
Acute bronchitis	Cases of acute bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
CDV-related hospital admissions	Number of cardiovascular-related hospitalizations
Upper respiratory symptoms	Episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes)
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
MRAD	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD)
Work loss days	Number of work days lost due to illness
Asthma exacerbations	Number of episodes with cough, shortness of breath, wheeze, and upper respiratory symptoms in asthmatic children

provide a high and low estimate of mortality associated with changes in ambient PM2.5. COBRA includes different mortality risk estimates for both adults and infants. Infant mortality is based on Woodruff et al. (1997). Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

Nonfatal heart attacks were linked by Peters et al. (2001) to PM exposure. Nonfatal heart attacks were modeled separately from hospital admissions because of their lasting impact on long-term health care costs and earning. COBRA provides a high and low estimate of incidence for nonfatal heart attacks based on differing literature.

Hospital admissions include two major categories: respiratory (such as pneumonia and asthma) and cardiovascular (such as heart failure, ischemic heart disease). Using detailed hospital admission and discharge records, Sheppard et al. (1999) investigated asthma hospital emissions associated with PM, CO, and ozone, and Moolgavkar (2000, 2003)) found a relationship between hospital admissions and PM. COBRA includes separate risk factors for hospital admissions for people aged 18 to 64 and aged 65 and older.

Acute bronchitis, defined as coughing, chest discomfort, slight fever, and extreme tiredness lasting for a number of days, was found by Dockery et al. (1996) to be related to sulfates, particulate acidity, and, to a lesser extent, PM. COBRA estimates the episodes of acute bronchitis in children aged 8 to 12 from pollution using the findings from Dockery et al.

Upper respiratory symptoms include episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching or red eyes). Pope et al. (2002) found a relationship between PM and the incidence of a range of minor symptoms, including runny or stuffy nose; wet cough, and burning; aching or red eyes.

Lower respiratory symptoms in COBRA are based on Schwarz and Neas (2000) and focus primarily on children's exposure to pollution. Children were selected for the study based on indoor exposure to PM and other pollutants resulting from parental smoking and gas stoves. Episodes of lower respiratory symptoms are coughing, chest pain, phlegm, or wheezing.

Asthma related emergency room visits are primarily associated with children under the age of 18. Sheppard et al. (2003) found significant associations between asthma ER visits and PM and CO. To avoid double counting, hospitalization costs (discussed above) do not include the cost of admission to the emergency room.

Minor restricted activity days (MRAD) in COBRA were based on research by Ostro and Rothschild (1989). MRADs include days on which activity is reduced but not severely restricted (e.g., missing work or being confined to bed is too severe to be an MRAD). They estimated the incidence of MRADs for a national sample of the adult working population, aged 18 to 65, in metropolitan areas. Because this study is based on a “convenience “sample of nonelderly individuals, the impacts may be underestimated because the elderly are likely to be more susceptible to PM-related MRADs.

Work loss days were estimated by Ostro (1987) to be related to PM levels. Based on an annual national survey of people aged 18 to 65, Ostro found that 2-week average PM levels were significantly linked to work loss days. However, the findings showed some variability across years.

Asthma exacerbations estimates were pooled from Ostro et al. (2001) and Mar et al. (2004) to calculate impacts of changes in air quality on asthmatic children. Cough, wheeze, and shortness of breath are all considered to be exacerbations.

G.2.3 Changes in Health Effects Impacts

→ Changes in Moneta

COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint. The per-unit monetary values are described Appendix F of the COBRA user’s manual (U.S. EPA, 2012d). Estimation of the monetary unit values varies by the type of health effect. For example, reductions in the risk of premature mortality are monetized using value of statistical life estimates. Other endpoints such as hospital admissions use cost of illness units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering. COBRA allows users to choose between a discount rate of 3% or 7% to calculate the present value of health effects that may occur beyond the year 2017.

G.2.4 Limitations

It should be noted that COBRA does not incorporate effects of many pollutants, such as carbon emissions or mercury. This has two potential implications. First, other pollutants may cause or exacerbate health endpoints that are not included in COBRA. This would imply that reducing incidences of such health points are not captured. Second, pollutants other than those included in COBRA may also cause a higher number of incidences of the health effects that are part of the model. This is also not captured in this analysis. Thus, the economic value of health effects obtained from COBRA may be interpreted as a conservative estimate of the health benefits from reducing emissions.

Appendix H: Design of Knowledge Benefits Assessment

This appendix is provided in support of Section 7 of the report.[52] It outlines the project design used to trace the knowledge outputs of DOE-funded research in energy storage technologies (Li-ion, NiMH, and ultracapacitor) through multiple generations of technology.[53] A brief overview of patent citation analysis, which forms the basis for much of the work presented in Section 7, is provided for the reader who is less familiar with the approach. This overview is followed by a description of the techniques used to link the various data sets used in the knowledge assessment.

H.1 OVERVIEW OF PATENT CITATION ANALYSIS

The front page of a patent document contains a list of references to prior art. The purpose of these prior art

[52] Section 7 and accompanying Appendix H were contributed by Rosalie Ruegg of TIA Consulting, Inc. and Patrick Thomas of 1790 Analytics LLC. RTI had no role in the development of Section 7 and Appendix H.

[53] Patent references are not identified at the EERE program/subprogram level. Furthermore, certain patent databases referenced here are at the level of DOE, rather than the EERE program/subprogram (i.e., VTO). However, when the term "DOE-attributed patents" is used here, it is equivalent to Section 7's use of "VTO-attributed patents." The rationale is that VTO with its research programs in Li-ion, NiMH, and ultracapacitor technology will likely have funded most of the research in these fields. At the same time, it is possible that some of the patents may be attributable to SBIR or other DOE funding sources.

references is to detail the state of the art at the time of the patent application and to demonstrate how the new invention is original over and above this prior art. Prior art references may be made to many different types of public documents. A large number of the references are to earlier patents, while others are to scientific papers and various other types of printed documents such as technical reports.

The responsibility for adding prior art references differs across patent systems. 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. Patent examiners may then reference additional prior art that limits the claims of the patent for which an application is being filed. In contrast to this, in the European Patent Office (EPO), prior art references are added by the examiner, rather than the applicant. The number of prior art references on EPO patents thus tends to be much lower than the number on U.S. patents.

Patent citation analysis centers on the links between generations of patents that are made by these prior art references. This type of analysis is based on the idea that the prior art referenced by patents has had some influence, (however slight or great), on the development of these patents. The prior art is thus regarded as part of the foundation for the later inventions.

In assessing the influence of individual patents, citation analysis centers on the idea that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular interest or importance. As such, they form the basis for many new innovations and research efforts, such that they are cited frequently by later patents. Although it is not true to say that every highly cited patent is important or that every infrequently cited patent is trivial, many research studies have shown a correlation between patent citations and measures of technological and scientific importance. For additional background on the use of patent citation analysis, including a summary of validation studies supporting its use, see Breitzman A. & Mogee M. "The many applications of patent analysis." *Journal of Information Science*, 28(3), 2002, 187-205.

Patent citation analysis has also been used extensively to trace 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. For example, the analysis presented in Section 7 uses citations from patents to earlier patents and papers to trace the influence of DOE-funded energy storage research. These represent direct links between DOE-funded research and subsequent patents and the technological developments these represent.

The idea behind this analysis is that the later patents have built in some way on the previous DOE-funded research. By determining how frequently DOE-funded Li-ion, NiMH, and ultracapacitor patents have been cited by subsequent patents, it is thus possible to evaluate the extent to which DOE funding forms a foundation for various technologies both inside and outside Li-ion, NiMH, and ultracapacitors.

H.2 FORWARD AND BACKWARD TRACING

As noted above, the purpose of this analysis is to trace the influence of DOE-funded energy storage (namely, Li-ion, NiMH, and ultracapacitor) research on subsequent developments both inside and outside these technologies. There are two approaches to such a tracing study—forward tracing and backward tracing—each of which has a slightly different objective.

The idea of forward tracing is to take a given body of research and trace the influence of this research on subsequent technological developments without restriction in terms of technology or industry area. In the context of the current analysis, forward tracing involves first identifying all Li-ion, NiMH, and ultracapacitor patents resulting from research programs funded by DOE, plus scientific papers resulting from related DOE research funding. The impact of these patents and papers on subsequent generations of technology is then evaluated. Because this tracing is not restricted to later Li-ion, NiMH, and ultracapacitor patents, it shows how the influence of a body of research may extend beyond its immediate area of potential application. Hence, the purpose of the forward tracing element of this project is to determine the impact of DOE-funded Li-ion, NiMH, and ultracapacitor research on developments both inside and outside these energy storage technologies.

Backward tracing, as the name suggests, looks backward over time. The idea of backward tracing is to take a particular technology, product, or industry and trace back to identify the earlier technologies on which it has built. In the context of this assessment, the analysis identified the companies with the largest portfolios of Li-ion, NiMH, and ultracapacitor patents, respectively, and then traced backward starting from these portfolios. This makes it possible to determine the extent to which the leading commercial innovators in each area have built on earlier DOE-funded research in developing their Li-ion, NiMH, and ultracapacitor technologies.

H.3 TRACING MULTIPLE GENERATIONS OF CITATION LINKS

The simplest form of tracing study is one based on a single generation of citation links between documents. Such a study identifies documents that cite, or are cited by, a given set of patents as prior art. The knowledge assessment described in Section 7 extends the tracing beyond this by adding a second generation of citation links. This means that the tracing goes forward through two generations of citations starting from DOE-funded Li-ion, NiMH, and ultracapacitor patents, plus DOE-funded papers. It also means that the tracing goes backward through two generations starting from the sets of Li-ion, NiMH, and ultracapacitor patents owned by the leading companies in these technology. Hence, there are two types of links between DOE patents and papers and subsequent generations of patents:

1. **Direct Links**: cases where a patent cites a DOE-funded Li-ion, NiMH, or ultracapacitor patent, or a DOE-funded paper, as prior art.

2. **Indirect Links**: cases where a patent cites an earlier patent, which in turn cites a DOE-funded Li-ion, NiMH, or ultracapacitor patent, or a DOE-funded paper. The DOE patent or paper is thus linked indirectly to the subsequent patent.

The idea behind adding the second generation of citations is that agencies such as DOE often support basic scientific research. It may take time, and multiple generations of research, for this basic research to be used in an applied technology, such as that described in a patent. Introducing a second generation of citations provides greater access to these indirect links between basic research and applied technology.

One potential problem with adding this second generation of citations must be acknowledged. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. This problem is that, if one uses enough generations of links, eventually almost every node in the network will be linked. The most famous example of this is the idea that every person is within six links of any other person in the world. By the same logic, if one takes a starting set of patents and extends the network of prior art references far enough, eventually almost all earlier patents will be linked to this starting set. Years of experience in developing extensive databases in intellectual property and working with corporate and government clients to evaluate funding impact and identify innovation indicate that using two generations of citation links is appropriate for tracing studies such as this. Adding any further generations may bring in too many documents with little connection to the starting patent sets.[54]

H.4 CONSTRUCTING PATENT FAMILIES

Organizations often file for protection of their inventions across multiple patent systems. For example, a U.S. company may file to protect a given invention in the United States and also file for protection of this invention in other countries. Also, inventors may apply for a series of patents in the same country based on the same underlying invention. As a result, there may be multiple patent documents resulting from the same invention. One or more U.S., EPO, and WIPO patents may result from a single invention.

To avoid counting the same inventions multiple times, it is necessary to construct patent families. A patent family contains all of the patents and patent applications that result from the same original patent application (named the priority application). A patent family may include patents/applications

[54] Patrick Thomas and Anthony Breitzman (2006).

from multiple countries and also multiple patents/applications from the same country.

Preparation of the knowledge assessment in Section 7 entailed constructing patent families (1) for VTO/DOE, (2) for the sets of leading energy storage companies, and (3) also for all of the patents/applications linked through citations to DOE. Constructing these patent families required matching the priority documents of the USPO, EPO, and WIPO patents/applications, in order to group them into the appropriate families. This task was achieved using fuzzy matching algorithms, along with a small amount of manual matching, because priority documents have different number formats in different patent systems. It should be noted that the priority document need not necessarily be a U.S., EPO, or WIPO application. For example, a Japanese patent application may result in U.S., EPO, and WIPO patents/applications, which are grouped in the same patent family because they share the same Japanese priority document.

H.5 DATA SETS FOR ANALYSIS

An objective of the analysis is to determine the impact of DOE-funded energy storage research on subsequent developments both within and outside energy storage. In order to carry out such an analysis, it was necessary to construct different data sets. Specifically, the backward tracing starts from the sets of all Li-ion, NiMH, and ultracapacitor patents owned by leading innovator companies in combined energy storage. Meanwhile, the forward tracing starts from the sets of energy storage patents (plus papers) attributed to research funded by DOE.

H.6 IDENTIFYING ENERGY STORAGE (LI-ION, NIMH, AND ULTRACAPACITOR) PATENTS

In order to define the starting patent sets (i.e., the sets of Li-ion, NiMH, and ultracapacitor patents owned by leading companies, and the sets of Li-ion, NiMH, and ultracapacitor patents attributed to DOE), it was first necessary to define broader patent sets containing all patents in these technologies. These patent sets were constructed using patent filters consisting of combinations of keywords and International Patent Classifications (IPCs). Restricting the search by patent classification reduces the likelihood of including irrelevant patents using the same terms. For example, the term "rocking chair" has a specific meaning when applied to battery technology, but it also has a much more traditional meaning as a piece of furniture.

The filters used to identify Li-ion, NiMH, and ultracapacitors are outlined below. In the keywords and phrases used in these filters, * is a wildcard denoting unlimited characters, while ? is a wildcard denoting zero or one character, including a space. Hence, the search term Ni(?)MH covers Ni-MH, Ni MH, Ni/MH etc., while the search term ultra(?)capacit* covers ultracapacitor, ultra-capacitor, ultra capacitors, ultracapacitive, etc.

Identifying Li-ion Battery Patents—The filter used to identify Li-ion battery patents consists of two main elements (see Table H-1). The first element is an IPC (H01M 10/0525) directed specifically to such batteries. Patents in this class were included in the Li-ion set with no further keyword restriction. The second element takes broader IPCs related to batteries (H01M and H02J 7), electric vehicles (B60L 11/18), and coatings (B05D 5/12) and combines these IPCs with keywords directed specifically to Li-ion battery chemistries. In addition, a manual check of patents that use these keywords, but are in other IPCs, was done, and this added a small number of additional relevant patents.

This process resulted in the identification in total of 3,003 U.S. Li-ion patents, 2,019 EPO Li-ion patents, and 2,930 WIPO Li-ion patents issued/published between January 1976 and December 2012. Next, these 7,952 patents were grouped into 4,782 patent families.

Identifying NiMH Battery Patents—Unlike in Li-ion, there is no specific IPC directed to NiMH batteries. The main NiMH filter (see Table H-2) thus consists of the broader IPCs used in the Li-ion filter, combined with different versions of NiMH and nickel metal hydride. Given the lack of a specific IPC directed to NiMH, an extra effort was made to identify relevant patents. Specifically, this included experimenting to extend the search to include claims along with titles and abstracts, and used various combinations of keywords, resulting in additional patents being identified for possible inclusion in the NiMH set, which were then manually checked. Even so, the NiMH patent set remains the smallest of the three technologies.

Table H-1. Filter for Identifying Li-ion Battery Patents

***IPC* =** H01M 10/0525—Rocking-chair batteries, i.e., batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries

OR

***IPC* =**

H01M—Process or means e.g., batteries, for the direct conversion of chemical energy into electrical energy

H02J 7—Circuit arrangements for charging or depolarising batteries or for supplying loads from batteries

B60L 11/18—Propulsion of electrically propelled vehicles, using power supplied from primary cells, secondary cells, or fuel cells

B05D 5/12—Processes for applying liquids or other fluent materials to surfaces to obtain a coating with specific electrical properties

AND

***Title/Abstract* =**

Lithium(?)ion

Li(?)ion

Rocking(?)chair

Lithium(?)cobalt(?)oxide

LiCoO2

Lithium(?)nickel(?)cobalt*

Li(?)Ni(?)Co*

Lithium(?)nickel(?)manganese*

Lithium(?)iron(?)phosphate

LiFePO*

Lithium(?)manganese(?)spinel*

LiMnO*

Lithium(?)titan*

LiTiO*

Manganese(?)titan*

LiMn(?)Ni*

PLUS: Identified patents in other IPCs using these keywords and added selected patents after manual checking.

Table H-2. Filter for Identifying NiMH Battery Patents

Filter Details
IPC =
H01M—Process or means e.g., batteries, for the direct conversion of chemical energy into electrical energy
H02J 7—Circuit arrangements for charging or depolarising batteries or for supplying loads from batteries
B60L 11/18—Propulsion of electrically propelled vehicles, using power supplied from primary cells, secondary cells, or fuel cells
B05D 5/12—Processes for applying liquids or other fluent materials to surfaces to obtain a coating with specific electrical properties
AND
Title/Abstract =
Nickel(?)metal(?)hydride
NiMH
Ni(?)MH
PLUS: Identified patents using these keywords in claims, but not title/abstract, and added selected patents after manual checking. Most patents were not relevant, but described other technologies (e.g., packaging, control systems, testers/diagnostics) that can apply to various battery technologies, and list NiMH as one such technology.
PLUS: Identified patents in other IPCs using the NiMH keywords and added selected patents after manual checking.
PLUS: Identified patents referring to “metal hydride” in title/abstract and added selected patents after manual checking (because metal hydrides have other applications, such as fuel cells).
PLUS: Identified patents using the terms nickel hydroxide, nickel oxyhydroxide, hydrogen storing alloys, AB5, AB2 in their title/abstract, and added selected patents after manual checking

This process yielded a total of 330 U.S. NiMH patents, 189 EP NiMH patents, and 113 WO NiMH patents issued/published between January 1976 and December 2012. These 632 patents were grouped into 406 patent families.

Identifying Ultracapacitor Patents—The filter used to identify ultracapacitor patents consists of three main elements (see Table H-3). The first element is a series of IPCs specifically directed to different elements of double-layer capacitors (note that these IPCs have been moved in the most recent version of the IPC, but this does not affect the analysis carried out here). Patents in these IPCs are included in the ultracapacitor set without further keyword restrictions. The second element is a

Table H-3. Filter for Identifying Ultracapacitor Patents

IPC =

H01G 9/155—Double-layer capacitors

H01G 9/016—Electrolytic capacitor terminals specially adapted for double-layer capacitors

H01G 9/038—Electrolytic capacitor electrolytes specially adapted for double-layer capacitors

H01G 9/058—Electrolytic capacitor electrodes specially adapted for double-layer capacitors

OR

***Title/Abstract* =**

Ultra(?)capacitor*

Super(?)capacitor*

Pseudo(?)capacitor*

Electric(?)Double(?)layer(?)capacitor*

Electrical(?)Double(?)layer(?)capacitor*

Electrochemical(?)Double(?)layer(?)capacitor*

EDLC*

OR

***IPC* =**

H01G—Capacitors

AND

***Title/Abstract* =**

Ultra(?)capacit*

Super(?)capacit*

Pseudo(?)capacity*

(Electric/Electrical/Electrochemical) Double(?)layer(?)capacity*

PLUS: Identified patents in IPC H01G (Capacitors) that refer to materials such as activated carbon, activated charcoal, microporous carbon, conducting polymer, carbon polymer, and added a small number of relevant patents after manual checking.

series of keywords that are used without IPC restriction, because these terms, such as ultracapacitor and supercapacitor, have very specific meanings. The third element is a combination of a general Capacitors IPC (H01G) with stemmed versions of the keywords, which served to pick up a few additional patents. A check of IPC H01G for materials used in ultracapacitors, after manual checking, served to add a few more patents.

This process yielded the identification of 1,397 U.S. ultracapacitor patents, 942 EP ultracapacitor patents, and 1,552 WO ultracapacitor patents issued/published between

January 1976 and December 2012. These 3,891 patents were grouped into 2,609 patent families.

H.7 IDENTIFYING LI-ION, NIMH, AND ULTRACAPACITOR PATENTS ASSIGNED TO LEADING COMPANIES

Having constructed patent sets for Li-ion, NiMH, and ultracapacitors, the next step was to identify the 10 leading patenting organizations in combined energy storage. These companies are referred to in the results section as the “leading innovative companies” or “leading companies in energy storage.” This designation is based on patent portfolio size alone and is not a reflection of the number of units of a particular product sold, revenues, profits, or other characteristics. A fuller description would be the companies leading in patenting of energy storage, but this is a cumbersome description to use throughout the results section of the report. The 10 leading organizations in energy storage are shown in Table H-4.

Table H-4. 10 Leading Companies in Energy Storage

Parent Name	Number of Energy Storage Patent Families
Panasonic Corporation	618
Toyota Motor Company	213
NEC	163
Samsung	161
LG Chem Ltd.	147
Hitachi Ltd	146
Sony Corp	112
Valence	108
Asahi Glass	104
Greatbatch	93
Nisshinbo Holdings Inc.	39
Siemens Aktiengesellschaft	33
Corning Inc.	31
General Electric Company	28

H.8 IDENTIFYING VTO-ATTRIBUTED ENERGY STORAGE (LI-ION, NIMH AND ULTRACAPACITOR) PATENTS

As noted above, the forward tracing element of the analysis starts from the combined set of DOE-attributed Li-ion, NiMH, and ultracapacitor patents.[55] To construct these patent sets, it was necessary to first identify all patents funded by DOE. This DOE-funded patent set was then matched against the overall Li-ion, NiMH, and ultracapacitor patent sets described above, with the intersections representing the sets of DOE/VTO-attributed energy storage patents.

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 are likely to 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, acquisitions, etc.

Constructing a patent list for a government agency is more complicated, because the agency may fund research carried out at many different organizations. For example, DOE operates a number of laboratories and research centers, such as Ames, Argonne, Berkeley, Brookhaven, Livermore, Los Alamos, Oak Ridge, and Sandia. Patents emerging from these laboratories and research centers may be assigned to DOE. However, the patents may also be assigned to the organization that manages the laboratory or research center. For example, patents from Sandia may be assigned to Lockheed Martin or to Sandia Corporation, a wholly owned subsidiary of Lockheed Martin that manages and operates Sandia National Laboratories, while Livermore patents may be assigned to the University of California.

A further complication is that DOE not only funds research in its own labs and research centers, but it also funds research

[55] Note the use of the terms “DOE/VTO-funded research” and “DOE/VTO-attributed patents.” The reason for avoiding the term “DOE/VTO patents” or “DOE/VTO-funded patents” is the fact that although DOE funded much of the research that led to patents, it did not fund the patent filings and often was not the assignee.

carried out by private companies, universities, and other organizations. When this research results in patented inventions, these patents are likely to be assigned to the company or university carrying out the research, rather than to DOE.

Identifying DOE-Funded Patents—For the purpose of studies such as this, 1790 Analytics has constructed a database of DOE-attributed patents. These include patents assigned to DOE itself and patents assigned to individual labs, lab managers, and other organizations funded by DOE. The database was constructed using three primary sources:

1. ***OSTI Database***—The first source 1790 Analytics used was a database provided to it by DOE's Office of Scientific & Technical Information (OSTI) for use in DOE-related projects. This database 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 sponsor organization within DOE, and the U.S. patents that resulted from these DOE grants.

2. ***Patents assigned to DOE***—1790 Analytics identified a number of U.S. patents assigned to DOE that were not in the OSTI database, often because they have been issued since the latest update of the database. These patents were added to the list of DOE patents. Also a number of patents were identified with assignee names matching DOE labs, including Livermore, Argonne, Los Alamos, Brookhaven, and Sandia. These patents were added to the DOE list, after manual checking to remove patents assigned to organizations not related to DOE (e.g., Los Alamos Technical Associates, Livermore & Knight, Livermore Software Technology Corp).

3. ***Patents with DOE Government Interest***—A U.S. 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. 1790 Analytics identified all patents that refer to "Department of Energy," "Dept. of Energy," "DOE," "NREL," or "National Renewable Energy Lab*" in their Government Interest field. The company also identified patents that refer to government contracts beginning with DE- or ENG-, because these abbreviations typically denote DOE grants (It was necessary to remove a small number of non-DOE patents with DE- and ENG- grants—mainly NIH [DE-]

and NSF [ENG-]). Patents in this set that were not in the OSTI database, or assigned to DOE, were added to 1790's list of DOE patents.

The DOE patent database constructed from these three sources contains a total of 23,118 U.S. patents issued between January 1976 and December 2012. This patent set was then matched against the sets of Li-ion, NiMH, and ultracapacitor patents, resulting in a list of DOE-attributed U.S. patents in each of the technologies. Other family members from the US Patent and Trademark Office (USPTO), the European Patent Office (EPO), and the World Intellectual Property Organization (WIPO) were then attached to these patents. The numbers of DOE-funded Li-ion, NiMH, and ultracapacitor patents and patent families are shown in Table H-7.

One point to note in Table H-7 is the small number of DOE-funded NiMH patent families. DOE did provide extensive funding for the development of NiMH batteries to Energy Conversion Devices (ECD) and its subsidiary Ovonics Battery Company. ECD/Ovonics was granted a large number of NiMH patents (second only to Panasonic, as outlined later in the report). However, only a small fraction of these patents acknowledge DOE support, and only these patents are included in the DOE-attributed set. DOE funding may also have been beneficial to the research that resulted in other ECD/Ovonics NiMH patents, but, in the absence of an explicit link, these other patents are not included in the DOE set. Hence, the DOE-funded NiMH patent set is likely a very conservative listing.

Table H-7. Number of DOE-Funded Li-ion, NiMH and Ultracapacitor Patents and Patent Families

	# Patent Families	# USPTO Patents	# EPO Patents	# WIPO Patents
Li-ion	56	70	14	20
NiMH	9	15	11	5
Ultracapacitors	47	70	4	20

H.9 IDENTIFYING DOE-FUNDED LI-ION SCIENTIFIC PAPERS

In addition to the patent sets outlined above, TIA Consulting compiled a list of DOE-funded scientific papers from DOE annual reports issued 2000 TO 2012. Because of the period covered, most of the papers dealt with Li-ion technology and only a small number dealt with NiMH and ultracapacitors. After parsing this publication list, 2,281 distinct paper references were identified for which there was sufficient information to match to patent references (the publication list was in free text using the variable format from the annual report listings in which some references were incomplete). Most of these pertained to Li-ion. These paper references were then matched to the non-patent references contained in patents.

Because the list of DOE-funded papers used in the analysis pertained to Li-ion, they were included in the tracing alongside the list of DOE-attributed Li-ion patents. That is, the backward tracing included cases where a leading company's Li-ion patent cites a DOE-attributed Li-ion paper (i.e., patent-paper) and also cases where a leading company Li-ion patent cites a patent that in turn cites a DOE-attributed Li-ion paper (i.e., patent-patent-paper). Similarly, the forward tracing went through two generations of citing patents, starting with the DOE Li-ion papers.

Note that the analysis did not trace patent-paper-paper links (i.e., where a patent cites a paper that in turn cites a DOE paper), which would have required access to additional databases. Nor did it trace any paper-patent links (i.e., where a paper cites a patent), which are relatively rare.

H.10 PERFORMING THE ANALYSIS

The multiple processes described above in combination led to the ability to construct patent and paper sets covering combined DOE-attributed Li-ion, NiMH, and ultracapacitor research, as well as to construct patent sets for leading combined energy storage companies. In addition, it enabled the ability to link these document sets via citations. These document sets and the linkages between them form the basis for the results presented in Section 7 of this report.