

National Battery Collaborative (NBC)

Roadmap

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**Pre-Decisional Draft
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U.S. Department of Energy
Energy Efficiency and Renewable Energy

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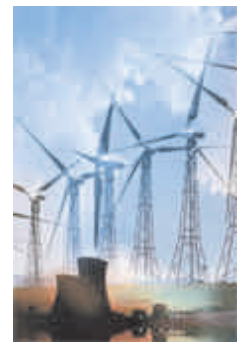
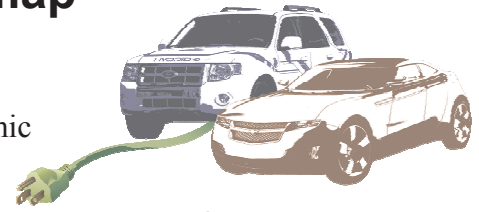
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National Battery Collaborative Roadmap

I. Background, Purpose, and Scope

Advanced batteries will play a significant role in the energy and economic security of the United States; therefore, ensuring a domestic supply of this technology is critical. Advanced batteries are essential for the development of electric drive, high-efficiency, light-duty, and heavy-duty vehicles. They are also seen as a critical enabling technology for the large scale deployment of renewable energy sources such as wind and solar. In addition, other applications, such as those in the defense and intelligence industries, would benefit from the use of advanced batteries. Current batteries for these applications are beginning to approach performance targets, but their price, size, and abuse tolerance do not yet meet market standards. In addition, nearly all high-volume advanced battery manufacturers are located in Asia. In contrast, the United States has limited manufacturing capability and a small number of trained battery engineers, scientists, and line workers. To be a global leader in the production and sale of advanced batteries, the U.S. must rapidly develop improved technology and establish a U.S.-based battery manufacturing capability.



The purpose of the National Battery Collaborative (NBC) is to help ensure that the United States leads the world in current and next generation battery technology and establishes a robust and dominant U.S.-based battery manufacturing industry. The NBC is a 6- to 8-year program with Department of Energy (DOE) funding up to \$4.5 billion, or approximately \$600 million per year. In addition, developers will be contributing matching funds in many of the development and facilities establishment areas. The work scope includes enhanced research and battery development activities, with a major concentration on advanced battery manufacturing technology and facilities construction.

The benefits of the NBC are as follows:

- Reduces U.S. dependence on foreign oil
- Reduces emissions of greenhouse gases from the domestic automotive fleet
- Creates a large number of jobs in advanced manufacturing
- Enables further market penetration of renewable energy sources such as wind and solar.
- Establishes the United States as a leader in a critical 21st century technology

Quantitative estimates for these benefits are being developed and will be presented in a later draft of this document. This remainder of this roadmap describes the activities of the NBC, as well as its structure, timing, cost, and high-level management plan.

II. Program Structure, Timing, and Cost

The NBC is composed of two parallel activities that will occur throughout the 6- to 8-year program:

- *Activity 1 – Enable U.S.-based Battery Manufacturing.* This activity will facilitate and support the establishment of a significant domestic battery manufacturing capability in the

United States. It includes researching and advancing cutting edge manufacturing processes, enabling all needed supply chain components, including materials suppliers, and constructing and equipping manufacturing facilities.

- *Activity 2 – Enhance Battery Research and Development Base.* This activity will establish the United States as a world leader in advanced battery technology. This activity includes improving near-commercial-ready materials and batteries, and developing and demonstrating next generation battery technology in prototype system-level designs and builds.

Figure 1 shows the DOE spending over the 6 to 8 years of this collaborative. It is assumed that the DOE Basic Energy Sciences (BES) will fund approximately \$75 million/year of basic research, with the DOE Office of Energy Efficiency and Renewable Energy (EERE) funding the remainder.

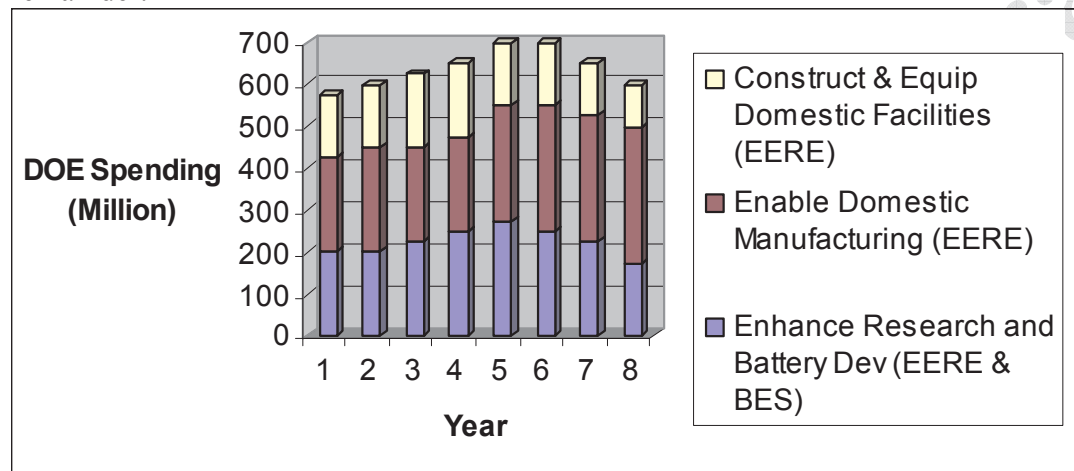


Figure 1. DOE spending vs. time for the NBC.

III. Management Plan

DOE EERE will have overall authority and responsibility for managing and implementing the NBC. The collaborative will be managed according to EERE's Strategic Management System, a framework that integrates planning, budget formulation, budget execution, and analysis and evaluation.

NBC Management Structure: The structure of the NBC management is shown in Figure 2. The NBC Program manager will develop and administer the program through the following steps:

- Provide policy and program direction and set overall program goals and objectives
- Authorize projects and establish and staff project management offices
- Align programs and projects with goals and objectives
- Conduct multi-year program planning and identify annual performance milestones
- Oversee, evaluate, and implement changes recommended through program reviews.

The program manager will be supported by two Energy Storage Research and Commercialization Centers (ESRACs), one focusing on research and development (R&D), and one focusing on manufacturing (see Figure 2). These centers will be staffed with U.S. researchers, engineers, and scientists from academia, national laboratories, and commercial

entities. The centers will help coordinate fundamental and applied research, testing, battery prototyping, manufacturing technology development, and facilities establishment. Their prime responsibility will be ensuring that new discoveries in one area are shared with the entire collaborative. They will also meet regularly to review the management and progress of the effort and report to DOE on potential improvements.

The basic research component of the NBC will be directed by DOE BES. The remainder of the program will be managed by DOE EERE staff, support scientists, and government/industry consortia, the Research and Development, and Domestic Manufacturing Teams in Figure 2.

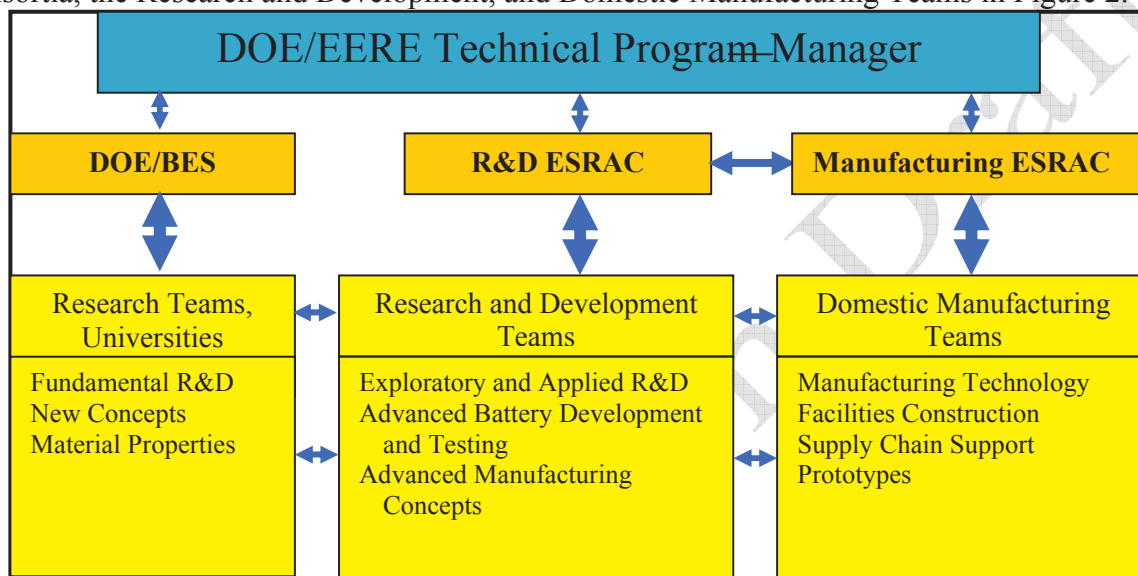


Figure 2. NBC management structure.

Program Implementation: The NBC program manager is responsible for managing resources consistent with cost, schedule, and technical progress. However, some of the approaches used to manage this large consortium will include the establishment of a new Program Management Office in EERE. In addition, government/industry consortia will be formed to support the manufacturing technology and battery supply chain efforts. Members of these consortia may include public sector experts from DOE, Department of Defense, intelligence, and other federal and state agencies; automotive manufacturers; stationary application users (utilities and renewable energy companies); battery manufacturers; materials suppliers; university professors; national laboratory technical leads; and other industry experts and subject matter experts.

Much of the work in this program will be sensitive to intellectual property (IP) concerns. To balance the need to engage industry while protecting each company's IP positions, several management and organization approaches will be used. U.S.-based developers and material suppliers will be invited to join R&D teams that will attempt to address concerns common to all consortia members. The research in these areas will be cost-shared by members, who would then have preferential access to the results of the work. Also, contracts with industry will be pursued for those research areas that are specific to one company's material or manufacturing process.

Program Analysis and Evaluation: At the onset of the program, a comprehensive cost benefit analysis will be performed to evaluate the various research topics proposed in this roadmap against their likely benefits, such as job creation, reduction of our dependence on foreign oil, and other benefits. The NBC program manager will also use technology and marketplace analysis tools to periodically evaluate the program's overall direction and technologies being researched and developed.

In accordance with EERE policy, program reviews will be held each year. Evaluations will be conducted at all levels of the effort, from each specific project up to the entire program. Peer reviews will be conducted by teams of public and private sector experts. The program manager will use the input of the review teams to evaluate progress, and when required, initiate corrective action to keep programs on target.

Program management will also monitor progress through the review of quarterly progress reports (as is also done presently in the energy storage program). The specific activities to be performed by the program managers include the following:

- Evaluate program variances from expected progress and initiate corrective actions
- Review project portfolio performance against established baselines and targets
- Support corporate and departmental evaluation efforts
- Identify significant variances in program results and recommend corrective actions
- Establish an evaluation plan and ensure adequate peer reviews of program progress.

IV. Summary Energy Storage Targets and Barriers

Summary requirements for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs) are given in Table 1. These goals will be periodically revisited and re-evaluated using advanced analysis and modeling tools.

Table 1. End-of-life targets of energy storage systems for HEVs, PHEVs, and EVs.

FreedomCAR Energy Storage Goals		HEV	PHEV	EV
Characteristics	Unit			
Equivalent Electric Range	miles	NA	10–40	200–300
Discharge Pulse Power	kW	25–40 for 10 sec	38–50	80
Regen Pulse Power	kW	20–25 for 10 sec	25–30	40
Recharge Rate	kW	NA	1.4–2.8	5–10
Cold Cranking Power @ -30°C	kW	5–7 for 2 sec	7 for 2 sec	NA
Available Energy	kWh	0.3–0.5	3.5–11.6	30–40
Calendar Life	year	15	10+	10
Cycle Life	cycle	300k, shallow cycling	3,000–5,000, deep discharge cycles	750, deep discharge cycles
Maximum System Weight	kg	40–60	60–120	300
Maximum System Volume	liter	32–45	40–80	133
Operating Temperature Range	°C	-30 to +52	-30 to +52	-40 to +85
Selling Price 100k/yr	\$	500–800	\$1,700–3,400	\$4,000

PHEV Battery Barriers: PHEV batteries face many of the same challenges associated with HEV batteries (uncertain calendar life, cost, abuse tolerance) plus additional challenges with energy density and specific energy. There is also concern that the deep cycling required of a PHEV battery all-electric range operation will be more difficult than the shallow HEV cycling.

The Vehicle Technologies Program Program Office does not believe that NiMH systems will be able to meet the weight and volume targets of a PHEV battery with greater than a 10- or 20-mile range. Figure 3 illustrates why the DOE program is focused on Li-ion battery technologies. Although Li-ion batteries can provide the energy and power for a 10-mile system, 20- to 40-mile goals are very difficult even for them. The major challenges to developing and commercializing batteries for PHEVs are as follows:

- **Cost**—The current cost of Li-based batteries is approximately a factor of three to five times too high on a kWh basis. The main cost drivers are the high cost of raw materials and materials processing, the cost of cell and module packaging, and manufacturing costs.
- **Performance**—Much higher energy densities are needed (for the 40-mile or greater system) to both meet the volume and weight targets and to reduce the number of cells needed for an entire battery, thus reducing the system's cost. In addition, durability and reliability of current batteries needs to be assessed and possibly improved for use in passenger vehicles.

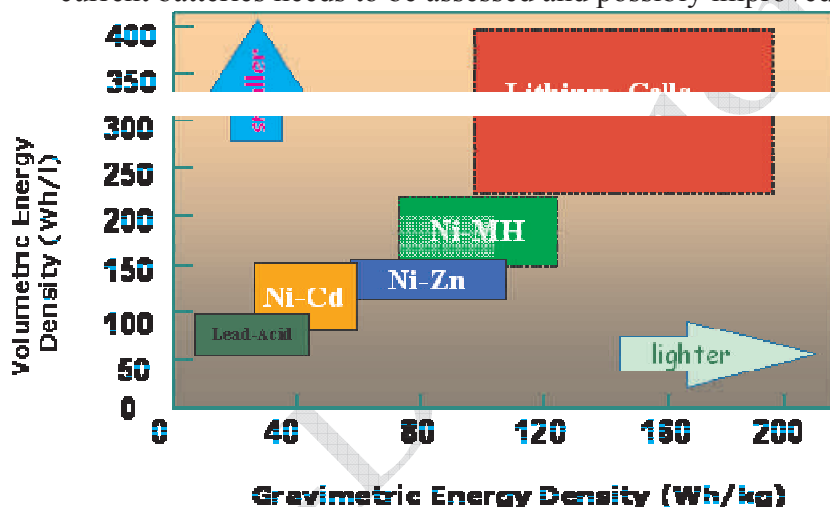


Figure 3. Gravimetric and volumetric energy densities for different battery technologies.

- **Abuse Tolerance**—Many Li batteries are not intrinsically tolerant to abusive conditions such as short circuits (including internal short circuits), overcharge, over discharge, crush, or exposure to fire and other high-temperature environments. The use of Li chemistries in these larger (energy) batteries increases the urgency with which these issues must be addressed.
- **Life**—Hybrid systems with conventional engines have a life target of 10 to 15 years, and battery life goals have been set to meet these targets. The goals of 300,000 HEV cycles and 5,000 deep discharge cycles are either unproven or are anticipated to be difficult. Specifically, the impact of combined EV/HEV cycling on battery life is unknown, and extended time at high state of charge (SOC) is predicted to limit battery life.

EV Battery Barriers: For EV batteries, the challenges are similar to those for PHEVs (weight, volume, calendar life, cost, and abuse tolerance), but the challenges are more difficult. Batteries

can be developed to meet these targets, but they will be a generation beyond the current state of the art. In general, the research to meet the challenges associated with EV batteries will build on work done on PHEV batteries, just as research for PHEVs will build on the battery technology used in HEVs.

Renewable Energy Storage Barriers: DOE is also considering the role of electrochemical energy storage systems for optimizing the use of renewable energy sources to reduce U.S. dependence on foreign oil. Affordable energy storage could enable increased market penetration for many renewable energy sources such as solar and wind. The targets of this application are different than those for transportation, and alternative electrochemical energy storage technologies need to be considered. In this application, energy density is less important than for PHEV and EV applications. Of paramount importance are (a) low cost, (b) long cycle and calendar life, (c) high system reliability, (d) low maintenance, (e) low self-discharge rates, and (f) high system efficiency. Although some of the new Li-ion battery technologies are viable candidates for this application, other technologies will be considered as well (e.g., flow batteries and high temperature battery technologies).

V. NBC Plan Details

This section presents the activities that will be performed as part of the NBC. The overall approach for how these various activities will interact and complement each other is shown in Figure 4. The overall goal of the work is to support and enable the establishment of a U.S. battery industry. The activities within the Enhance Battery Development & Research Base task area build on each other, with fundamental R&D breakthroughs informing the Advanced Energy Storage R&D teams, and with all those results being available to and enabling Advanced Battery Development.

That information, in turn, will be used to establish a U.S.-based Battery Manufacturing base. Advanced Manufacturing Process R&D will concentrate on both more efficient and cost-effective manufacturing of existing materials, as well as streamlined and high-volume manufacturing of advanced materials from the R&D activities. The advanced processes will be tested within the Product and Process Validation activity. Together, these will all help to ensure that the Construct and Equip Facilities task will result in manufacturing plants that will be producing the most advanced products at the lowest possible price. The Testing and Analysis activity will support nearly all aspects of this program.

Activity 1: Enable U.S. Based Battery Manufacturing (\$300–400M/year)

Objective: *Establish a U.S.-based battery manufacturing capability, including facilities construction and the material supply chain necessary to support high volume manufacturing*

This activity comprises three main components: (1) research & develop advanced battery manufacturing processes, (2) construct and equip domestic facilities, and (3) validate products and processes.



The *Construct and Equip Domestic Facilities* task (see Figure 4) will support developers who are trying to establish larger, faster, more efficient manufacturing facilities in the United States, plus developers and materials suppliers working to implement greatly improved materials to reduce the cost and improve the performance of HEV, PHEV, or EV batteries. In addition, this will include researching and building new machinery needed to implement improved manufacturing processes identified in the advanced battery manufacturing research area.

The following paragraphs provide more detail on these three areas.

Although many advanced materials have been developed under DOE's energy storage research programs, the introduction of these advanced materials into commercial products is hindered by the fact that the U.S. lags behind Asia, and to some extent Europe, in its ability to commercially

manufacture electrode materials and Li-ion cells. In order to help facilitate and accelerate competitive domestic manufacturing, the advanced manufacturing R&D program will include development of novel and optimized processing technologies, for both current state-of-the-art and advanced materials. This work will involve a close collaboration with the enhanced R&D activity described in Activity 2 and will include the active participation of battery developers, material and component suppliers, equipment manufacturers, universities, national laboratories, and end users such as automotive manufacturers and renewable energy technology producers and users.

The work in this area will be particularly sensitive to intellectual property concerns. Therefore, several management and organization approaches will be used. The technology development and transfer center described below will be one venue in which developers, materials suppliers, and researchers can gather to collaboratively research and test new ideas and technologies. In addition, DOE EERE will negotiate individual research and development contracts with commercial concerns to develop specific ideas. Finally, all developers and material suppliers may be invited to join a precompetitive research and development consortium, similar to the United States Advanced Battery Consortium (USABC), which will oversee and manage contracts that would attempt to address concerns common to all developers.

Several of the research topics that may be pursued include the following:

Improved formation: The formation process is one of the more time-consuming and costly steps in the battery production process. Formation is the process of slow cycling and aging at predefined temperatures that is carried out prior to delivering a cell to the customer. The formation process serves to “wet” the electrodes and to form a solid electrolyte interphase (SEI) layer on the anode particles that protects them from parasitic reactions with the electrolyte. The formation process often takes several days.

Means to significantly reduce formation time or completely eliminate this step will be investigated. Model electrode systems will be used along with *in situ* diagnostics techniques to understand the changes that occur at the interface during the charging process and to correlate these changes to the performance and life of the battery. With the collaboration of the battery industry, alternate formation techniques will be studied. Another topic that will be investigated is that of externally forming the SEI layer, thus eliminating the need for a formation step.

Dry electrode processing: Today, all electrodes start out as a wet mixture of components that are pasted onto a current collector and then processed through a large oven for drying. This process involves significant energy, time, and the use of environmentally harmful chemicals. Research will focus on revolutionary manufacturing techniques to permit the construction of electrodes through completely dry processes.

Optimized electrode formulations: The art of processing optimized electrodes will be studied and sufficiently understood, from a technical perspective, to introduce science into this process. For example, all battery manufacturers use binders and conductive additives in both anode and cathode electrodes. However, a complete understanding of how and why these materials work (or do not work) is not available. Therefore, an expanded cell-making capability will be

established to enable researchers to, among other topics, investigate the “why” of binder and conductive additive behavior. New science-based electrode processing technologies will be developed and optimized.

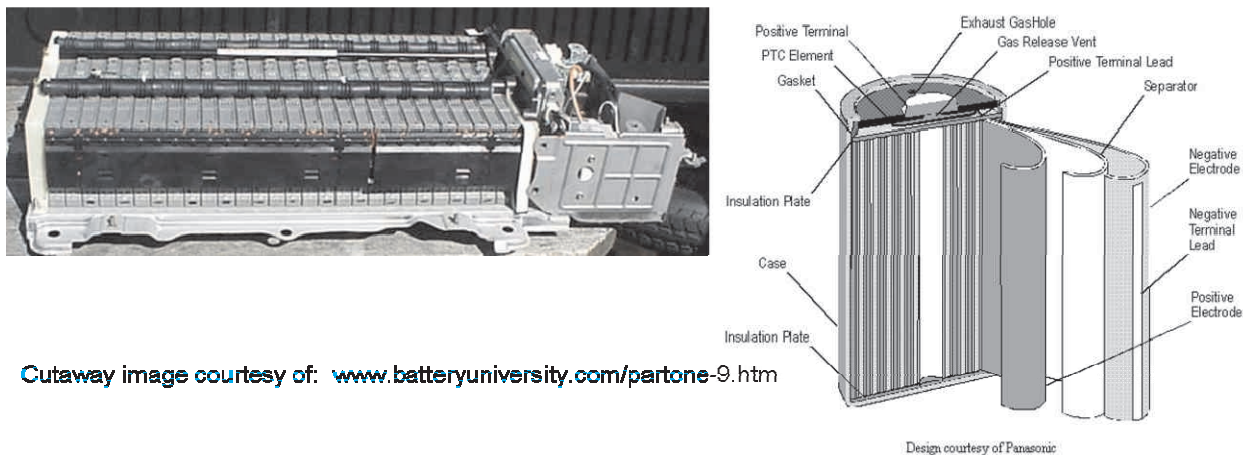
Particle size and shape control: Most active materials perform differently when they are produced with various primary and secondary particle sizes and shapes. This research will concentrate on quantifying the changes in performance with particle size and shape, and on developing processes for manufacturing the materials with the desired size and shape. This is one of the research areas that could significantly improve the performance of existing materials.

Cell sorting and batching: All major battery manufacturers currently sort and batch cells (based on energy, power, and other factors) before placing them into a complete battery. Eliminating this step would save significant time and money when manufacturing large battery systems. Thus, methods to dramatically improve the cell-to-cell consistency during high volume manufacturing will be investigated.

Manufacturing process scale up: This task area will research and test manufacturing processes for new and advanced high energy materials. A major emphasis will be to scale up processing technologies (which will already exist on the laboratory scale) to permit production of advanced materials in sufficient quantities so that they can be rapidly evaluated and considered for introduction into commercial products. The goal is to confirm the performance of new materials that are produced in larger quantities. This scale up to pilot plant quantities is one of the final steps in commercialization of new materials and will be supported through cost-shared programs.

When a new material is identified and developed, only small quantities (grams) are available from laboratory scale experiments. The next step is to prepare larger quantities of the material for evaluation in prototype cells. While the engineering process is based on the conditions established in the laboratory, the processing generally must be modified to produce larger quantity materials.

Revolutionary packaging: All Li-ion batteries (packages of many cells) use a standard packaging approach. Cells are first individually packaged in either a cylindrical can (e.g., 18650s) or a laminate pouch. These cells are then further bundled and packaged into a full battery system, which often involves hundreds of cells. The interconnects, voltage and temperature sensors, vents, and other hardware needed to manage each cell in this design add significant cost and manufacturing burden to the final product. In fact, only a very small percentage of the final product’s weight (approximately 25 to 30%) is due to the active materials that actually store the energy in the battery. Figure 5 shows a Prius battery pack with over 150 individual cells and a typical Li-ion cylindrical cell. The number of “non active” components in both the cell and the battery pack significantly increases the volume, weight, and cost of the finished product.



Cutaway image courtesy of: www.batteryuniversity.com/partone-9.htm

Figure 5. Prius battery pack (left) and cutaway image of a typical cylindrical cell (right).

In contrast, 12V lead-acid batteries contain six couples within a single housing, with no individual cell packaging. This approach greatly simplifies the manufacturing approach along with the cost and materials needed for each cell. In such a design, each Li-ion cell within the battery would consist of anode, cathode, electrolyte, separator, and current collectors. No individual cell packaging would be used. However, for this approach to become feasible, the following significant breakthroughs will be necessary and will be pursued:

- Parallel formation or pre-formation processing
- Enhanced sealing technologies
- Enhanced joining and welding technologies
- *In situ* diagnostics and sensor technology.

Electrode property measurement: High-speed electrode production is essential for high-volume (and thus lower cost) battery production. Electrodes are composed of materials that have complex interactions that strongly influence cell performance. As a result, the investigation of a variety of measurement techniques is required for the in-line and in-use measurement of electrode thickness, porosity, density, and other parameters. Fortunately, industries practicing continuous-process fabrication, such as those for paper and polymer films, employ a broad range of devices in the application of in-line process control. These techniques will be reviewed, understood, and modified or improved upon for use in Li-ion high-volume manufacturing.

In addition, there is a lack of understanding of the relationships between manufacturing tolerances for electrode and cell performance and durability. Thus, advanced nano sensor technology will be developed to measure the internal properties of a battery, such as temperature, voltage, and current, without adversely impacting its performance while in use. This information could aid developers, manufacturers, and researchers in evaluating the impact of electrode design changes on the internal workings of the cell, and eventually, on its performance and life. These measurements could also be used to validate the battery design and modeling tools (e.g., development and use of thin film or nano thermocouples to measure the internal temperature of cells, measuring voltage distribution throughout the layers of the cell using a thin insulating sheets etched with copper pads, development of tiny wireless sensors to communicate the voltage

and temperature values within the cell to outside for monitoring, and instantaneous measurement of state of the health of battery).

High-volume manufacturing equipment R&D: Another major area may involve research into advanced manufacturing equipment. Currently, nearly all high-volume Li-ion manufacturing machinery is produced in Japan. Plus, new manufacturing techniques (e.g. dry processing), may require new high-volume, high-speed machinery. Thus, R&D will concentrate on designing and enabling production of these machines for domestic manufacturers. Work in this area will be closely correlated with that in the technology development and transfer center described below.

Expanded prototype cell and battery production: Much of the work in this research area will require expanded capabilities and facilities for evaluating the materials, electrodes, and cells that will be produced in the enhanced R&D area and by materials and battery developers. Accelerated screening of new materials will also require expanded capabilities and facilities; therefore, these capabilities at national laboratories will be expanded. Included in these capabilities and facilities are prototype scale mixers, coaters, dryers, filling, and formation. Also included are the latest microscopic and spectroscopic tools for studying the chemical, physical, and structural properties of materials, both in the bulk and at the electrolyte/electrode interfaces. The needed equipment and facilities will be established to facilitate full-time access for members of the applied R&D program.

(2) Construct and Equip Domestic Facilities

Technology development and transfer centers: One approach for enabling and accelerating the deployment of advanced Li-ion materials, couples, battery packaging concepts, and manufacturing processes from research teams to industry is to establish technology development and transfer centers. These would be closely modeled on Sematech, the industry-government entity that greatly benefited the U.S. semiconductor industry. Industrial collaborators, including battery developers, battery integrators, materials suppliers, battery manufacturing equipment manufacturers, and end users (auto manufacturers, utilities, etc.), could work within the center to develop technology specific to their Li-ion cells or to work collaboratively on mutually beneficial technologies or manufacturing processes. New materials developed in national laboratories or universities would be available for evaluation and to speed transfer of new materials into the marketplace.

A technology transfer center and its major information exchanges with users are shown in Figure 6. Much of the actual work within the center could be cost shared. Proposals for projects would be submitted by battery or materials developers, and awards would be made based on technical merit and center availability.

The management of the center will be overseen by a subcomponent of the Manufacturing ESRAC, described in Section II of this roadmap. The center's management team will serve to coordinate material and technology transfer from research teams to materials suppliers and battery developers and would help to negotiate contractual arrangements to protect intellectual property while disseminating new information as widely as possible.

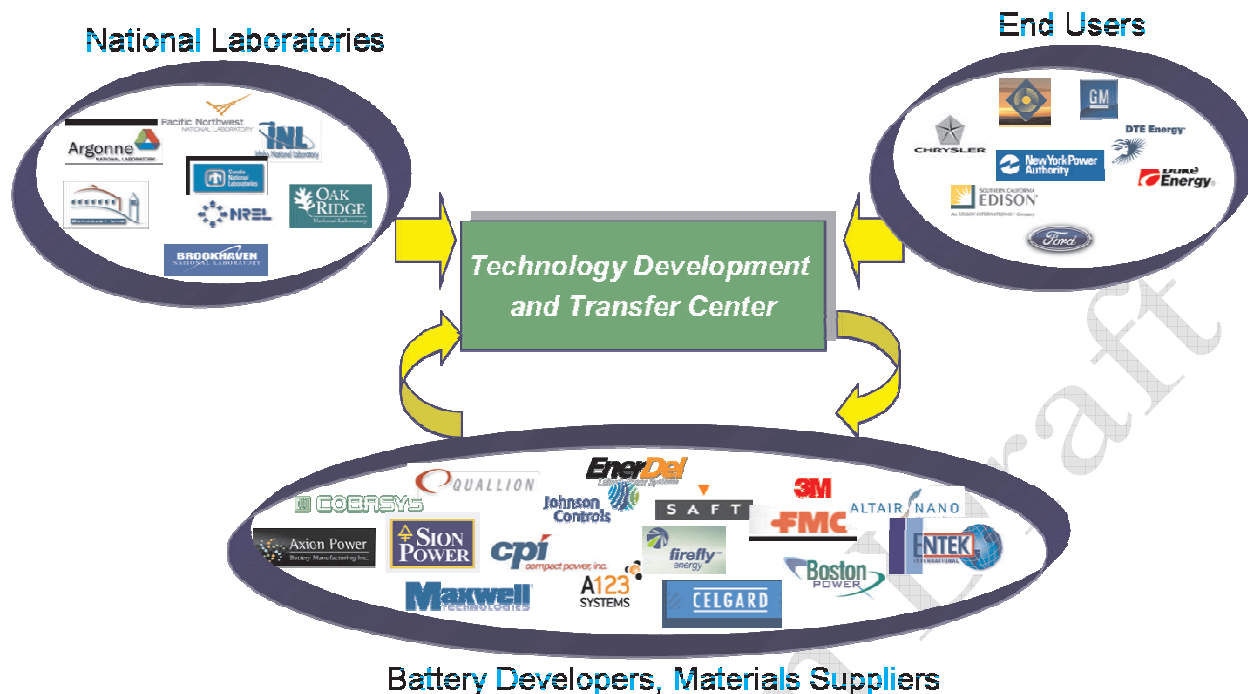


Figure 6. Technology transfer center.

This center will leverage resources across the commercial and research spectrum and focus the industry on manufacturing technology that will enable the manufacture of competitive products. The work in the center will focus on the following objectives:

- Develop manufacturing technology for continuous, heavily automated platforms that increase productivity and reduce manufacturing costs
- Provide access by U.S. companies to advanced and cutting-edge manufacturing tools and newly developed materials that will foster innovation
- Accelerate commercialization of innovative technologies as well as reduce the risk of market entry for domestic production capability for advanced materials and cells.

Areas of technology research, development, and evaluation in the center would include the following:

- Evaluation and prioritization of novel materials developed in both BES and EERE programs
- Manufacturing process R&D for incorporation of advanced materials into viable cells
- Improvement of the quality and resulting safety of advanced materials
- Expanded testing capabilities to support development of U.S. manufacturing capability
- Recycling technology for Li-ion battery materials
- R&D on the scale up of advanced materials and processing technologies for stationary energy storage, as part of a future activity of the center, in which the focus may include other advanced battery technologies, e.g., flow batteries and high temperature batteries
- Manufacturing process R&D for scalable (high-volume, least cost, quality controllable) production of advanced materials.

One goal of this final research area is to confirm the performance of new materials as they are produced in larger quantities. This scale up to pilot plant quantities is one of the final steps in commercialization of new materials and will be supported in full as a part of cost-shared programs with battery developers and materials suppliers. At this point in the development of a new material, the basic parameters are known from the pilot- and lab-scale operation. These must be scaled up over the pilot operations by a factor of 3 to 10 times, depending on the expected usage in cell assembly.

U.S.-based battery facilities: The near-term work in this area will concentrate on establishing facilities for technologies that are market ready or near market ready. Several technologies meet this criterion presently, such as batteries being sold into the HEV and niche PHEV markets. In the longer term, DOE EERE will work with developers to establish a domestic manufacturing base for emerging technologies. In particular, a goal of this effort will guarantee adequate product control during high-volume manufacturing, ensuring the production of consistently high-quality products.

This effort will support plant startup and initial operation, including the manufacture of an appropriate number of advanced batteries for testing and validation. It will also involve funding the construction and capitalization of the following facilities:

- Five to ten large-scale (~100,000 automotive batteries/year) battery manufacturing plants
- Appropriate supporting supplier production facilities
- Battery recycling facilities.

This task work will be at least partially dependent on the success of the “Niche markets” task described below. As mentioned there, it seems more likely for a major auto manufacturer to place an order with a domestic supplier if that supplier is already producing batteries for one or more other customers.

In order to facilitate construction of these facilities, NBC staff will work to streamline permitting and environmental review and, through the codes and standards work described elsewhere, will work with manufacturers and users to establish battery communications, recycling, and testing/validation standards.

Finally, this work will require close coordination with the manufacturing R&D activity and may require collaboration with teams within the technology development and transfer center.

Materials and component supplier facilities: Two scenarios relate to the construction of production facilities for Li-ion battery materials. One is expansion of an existing facility, and the other is the establishment of a new facility to produce a new higher performance material.

The construction of a production line to produce large quantities of new materials requires permitting the facility, installing equipment, and proving out the process on a large scale, which is a very expensive process. Even if the process works in a pilot operation, it still must be proven in large-scale production. This requires a much larger amount of starting materials and an increased number of people to operate the facility. Several runs are required to confirm that the

materials produced in large scale match exactly the characteristics of the materials from the pilot plant. Financial support to establish the manufacturing base will be provided as an extension of the research effort in developing new materials.

Increasing the production capability for an existing material differs from the development and production of new materials. Here, the requirement is that the materials have the same performance to serve expansion of an existing market. The conditions for producing a material are known; the requirements of time, temperature, and raw materials costs will have been established and can be duplicated in the new facility. There is minimal risk that the process will not produce satisfactory materials. In this instance a loan guarantee program will be offered.

Encouragement of niche markets for domestically produced batteries: DOE EERE will also work with other federal and state agencies and commercial concerns to identify an “entry market” for advanced batteries. Understandably, large auto manufacturers will be reluctant to purchase a battery that has not been tested over a significant number of vehicle miles. A number of federal, state, and private organizations could serve as starter markets. Among those are state fleets, city buses, utility fleets, USPS vehicles, FedEx, UPS, and other private fleets, and the U.S. military. An initial order of 1,000 to 10,000 batteries per year for several years could serve to establish the viability of a new battery, or of a new domestic facility producing an existing technology.

(3) Validate Products and Processes

Each new facility (both battery facility and material or component facility), new process, new material, new battery design, or new cell design, will require some level of testing and validation to ensure that the quality and performance of the products from that process or plant are sufficient for the intended application. Some of the tasks that will be pursued in this area include:

Codes and standards development: NBC staff will begin by holding a number of workshops with automotive manufacturers, utilities, renewable energy suppliers, battery developers, recyclers, and others to understand the scope of the codes and standards needed. Next, a series of workgroups will be formed to scope and draft each necessary code or standard. NBC’s role in the effort will be to facilitate the process and to fund the meeting logistics.

Test procedure development: DOE, in collaboration with industry, has established standard test procedures to evaluate the performance, life, and safety of batteries. However, additional test procedures, sensors, and analytical techniques will be needed to support battery manufacturers to diagnose, check, and improve the quality, performance, and life of mass produced batteries. These procedures, sensors, and analytical techniques should address battery components (electrodes, separators, electrolyte, hardware, and containers), cells, module, and pack during R&D, cell manufacturing and pack integration.

Another test procedure that may be needed is related to thermal performance. Existing batteries, particularly Li-ion, degrade very quickly at high temperatures and do not perform well at very low temperatures. Although some test procedures are available to evaluate thermal performance at various temperatures, a standard test procedure needs to be established for evaluating the

performance of battery thermal management systems. This procedure should consider the periods when the battery is not operating such as parked vehicle scenarios.

Finally, new test procedures may be needed for stationary (renewable, residential, and utility) applications.

Recycling and re-use R&D: One possible means of reducing battery cost is to plan for valuable recycling or reuse. To maximize this value, designing for that reuse or recycling may be critical. With this in mind, the NBC will fund joint R&D projects with participation by battery developers, auto manufacturers, utilities, other users, and recyclers to explore new design paradigms that will ensure maximum value of each high technology battery throughout its lifecycle.

Safety/qualification testing: The safety and qualification testing of cells and battery packs requires sophisticated test equipment, experienced and qualified test personnel as well as the manufacturing of quality cells and packs to be tested and evaluated. This will be supported by providing locations in the U.S. to qualify products and certify that they meet the required performance criteria. The cost of the equipment is significant, as is the cost of the number of cells and packs required for statistically significant qualification tests. The testing is essential to ensure the safe operation of the batteries when in actual use in a vehicle.

Benchmark testing: This task is to characterize the performance of selected batteries not yet under large-scale development. Testing will use standard FreedomCAR test procedures, and results will be reported against the same criteria used for evaluating FreedomCAR battery development progress. Systems of interest include: Li-ion and competing technologies.

Activity 2: Enhance Battery Development and Research Base

(\$150-250M/year, which includes ~\$75M/year from BES)

Objective: Establish the U.S. as the World Leader in Battery Technology.

(1) Develop Advanced Batteries

Battery development is the step within the R&D process in which technology transitions from research to development of prototypes produced in a manufacturing environment. A new material is typically first prepared in the laboratory in quantities of a few grams. Its potential as a battery component is evaluated in cells that are built by hand. Before a material can be adopted in batteries that will be produced in large numbers, the process must be transferred to industrial equipment and standardized to give a reproducible product. An example of this process is the ongoing attempt by Enerdel Inc. to commercialize a new lithium titanate anode material developed at Argonne National Laboratory.

Battery development will be done primarily by industry through cost shared contracts awarded on a competitive basis. The Vehicle Technologies Program Office has a strong history of working with the battery industry both through a cooperative agreement with the USABC and through direct contracts. In these efforts, the government's support has been leveraged by cost sharing by industry, typically at the 50% level. In the NBC, materials and cell design may

originate in the enhanced R&D activity and will transition from battery development into manufacturing development.

The battery development process is relatively mature for NiMH batteries for use in HEVs and is approaching maturity for Li-ion batteries for the same vehicles. Additional Li-ion development efforts will need to be funded to recognize the benefits of new materials now under development. Continued development is also necessary to reduce the cost and improve the safety of current products.

The purpose of this phase is to identify battery technologies and associated manufacturing concepts that have the potential for meeting and exceeding the cost and performance goals. The expectation is that individual proposals will be submitted by teams led by a battery manufacturer and preferably include automotive companies and material suppliers, and may also include equipment manufacturers. The number of cost shared contracts to be awarded will depend on a number of factors, including the NBC budget, the availability of new materials, new material suppliers, new cell or battery designs, and companies willing to invest in improving an existing technology or implementing a new one.

No matter how many contracts are funded, each must deliver (a) battery hardware for testing against HEV and EV battery targets, (b) a complete battery manufacturing facility design including equipment specifications and with associated cost, (c) a battery cost model, and (d) a battery recycling and/or secondary use plan. These factors will be used to select proposals for additional or follow-on funding and for facilities construction support.

Some specific technologies, including materials and new cell or battery designs, which EERE believes could be pursued under this activity in the short term include but are not limited to:

- High voltage nickelate cathodes or high voltage composite cathodes
- Alloy graphite composite anodes
- Electrode materials with precisely defined and designed size and shape (in collaboration with the manufacturing R&D task)
- High voltage and solid polymer composite electrolytes
- Low cost separators offering enhanced abuse tolerance and performance
- Electrodes with binders and conductive additives defined for use with the specific active materials (in collaboration with the manufacturing R&D task)
- Low cost couples that offer less than revolutionary performance gains but that meet or nearly meet performance goals at substantially reduced cost such as asymmetric ultracapacitors. Asymmetric ultracapacitors have one faradaic electrode such as graphite and one non-faradaic electrode such as activated carbon.

Additional research topics that might be pursued include:

Developing a battery life gauge: Battery developers and users require the ability to accurately predict battery life. Currently, this is done empirically using a significant amount of data, onboard measurement and adaptive algorithms. This work is repeated by different users for different chemistries and batteries. It is proposed to develop a precompetitive battery life gauge

to accurately monitor battery health. The gauge is envisioned to be composed of some combination of hardware (internal sensors and electronics circuitry) and software (energy counters and adaptive algorithms). The software would be based on the battery life data collected at various conditions (SOC, temperature) and rates. In addition to flagging maintenance actions and enabling adaption to battery state-of-health, life-gauge readings would help determine the value of the battery for secondary-use markets (such as stationary energy storage) once the first-use life is complete.

Developing a CAD/CAM software toolkit for battery design: Electrochemical, performance, and thermal design software is beginning to reach the stage of maturity at which users believe that they might be integrated to form a full battery design suite. The process of testing new materials in multiple cell sizes, in multiple battery pack designs, and over many months is extremely time consuming, expensive, and ad-hoc. This software suite would include materials properties, electrode design, pack design for thermal management purposes, usage profiles, and aging data as input, and could greatly speed the design of new batteries and provide critical guidance to developers.

(2) Perform Advanced Energy Storage R&D

The advanced energy storage R&D activity will occupy a unique position in the NBC. This portion of the NBC will connect the long-term/fundamental research of the BES effort to the battery development activities. With participants from leading U.S. universities, national laboratories, and industry, this activity will establish a framework for improving battery performance by connecting the fundamental to the applied to the full battery system.

Under the NBC, advanced energy storage R&D will be conducted under three initiatives that will accelerate the pace at which HEVs, PHEVs, and EVs will arrive in the marketplace. At the same time, we will strengthen the connection between the long-term focus of the BES effort and the applied needs of the battery/materials industry to establish a methodology for the rapid commercialization of new, promising materials. The work planned in this area is described below.

i. New materials and electrochemical couples: The current research program has been developing and continues to develop many advanced materials and cell-level technologies. These efforts will be expanded and will include, but not be limited to:

- Metal oxide anodes and/or metal anodes that operate by multiple electron transfer processes
- Higher voltage cathodes and cathodes that operate by multiple electron transfer processes
- Higher voltage electrolyte systems, preferably nonflammable, and that include new polymer electrolyte systems
- More stable electrode/electrolyte interfaces e.g., the development of functionalized coatings.

Following are some of the specific approaches that will be pursued:

Optimization of material properties across multiple length scales: Over the last five years, the battery community has come to recognize the importance of nanoparticles as a means of enhancing energy storage. Examples of materials with enhanced performance due to nano-

scaling include the LiFePO_4 cathode and a $\text{Li}_4\text{Ti}_5\text{O}_{12}$ anode, both recently commercialized. On the other hand, for materials such as graphite anodes, the instability of the electrolyte at the charging voltage necessitates minimization of the surface area by using μm -sized particles. The processes needed to make electrodes and study them depend on the size of the materials. Therefore, battery materials will need to be understood across multiple length scales, Figure 7.

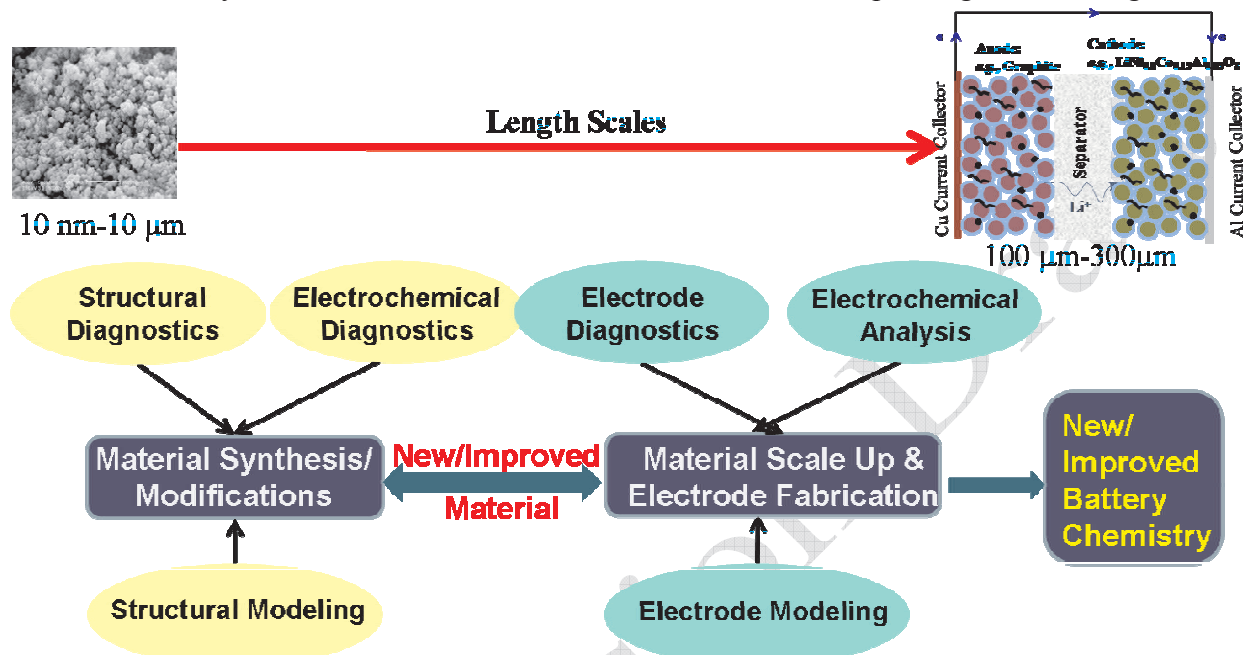


Figure 7. Study of materials and electrodes over multiple length scales.

With this in mind, we will further strengthen our existing methodology of studying material characteristics by using a combination of synthesis, diagnostics, and structural modeling, and will use these results to improve the material by modifying its inherent characteristics. This iterative process will lead to improved materials. Close interactions will be maintained with the researchers in the BES Program both to identify new materials and to use advanced *in situ* diagnostics to probe the surface and nature of materials in the nanoscale. Researchers will then take these materials to the electrode level.

Theory-driven identification and development of new materials: Over the last few years there has been tremendous improvement in the area of using *ab initio* modeling to identify the performance of new materials. This provides a direct way of predicting the energy density of new materials without the need for extensive experimentation. We will leverage this new capability and design a program where theory will be the core to new materials development with support from materials synthesis and diagnostics to check the validity of the predictions. We expect close collaboration with materials-development companies to aid in large-scale synthesis of promising materials. In addition, as new modeling tools are developed in the BES Program (for example, methods to quantify charge transfer at interfaces) they will be implemented to make better predictions. The Program's strong emphasis on length-scale studies means that promising materials will be tested under optimized cell-level conditions and the parameters from *ab initio* methods will be used in macroscopic models to provide true model-based materials development. New high-energy and high-power materials will be the focus of this effort.

Development of protected SEI layer: Degradation of the SEI layer in high-energy Li-ion cells leads to capacity and power loss over time. A study to characterize electrode surface coatings could help increase the life of batteries. For example, if one could develop a protective coating to create an “artificial SEI” layer over and around the electrode particles that is stable and elastic, the battery life could be drastically improved.

ii. Advanced diagnostics—New diagnostics efforts will include:

In situ diagnostics on model electrodes with emphasis on the nanoscale: While there have been numerous attempts over the years to understand battery materials through various diagnostic techniques, it has become clear that *ex situ* studies (where the battery is disassembled and then studied) have only limited applicability and that most phenomena of importance are better studied *in situ* (i.e., during battery operation). However, studies of materials *in situ* are complicated because introduction of the diagnostics probe could change the electrode, thereby introducing artifacts. Moreover, most battery electrodes are porous, which makes probing the diffuse interface difficult. We propose to initiate a new effort to devise ways to understand changes that occur at the interface and in quantifying differences between the surface and the bulk in nanoscale materials. This task would involve finding new ways to fabricate battery electrodes to study the interface, new cell designs on which to perform the *in situ* studies, and the use of nanotechnology to modify the morphology of the interface to study the response. Working closely with the applied program, we anticipate uncovering the fundamental issues that underlie the poor abuse tolerance and life issues of batteries, and finding new ways to alleviate these challenges (e.g., by chemical or morphology changes or using nanoscale coatings).

Non-destructive testing: 3-D X-Ray Computed Tomography could be used for nondestructive and nonintrusive internal imaging of batteries and their components. This device could help developers and manufacturers evaluate design uniformity and quality of material structure and density, material loading uniformity, etc. Quantification of thermal contacts and its uniformity between cell components could be investigated. *In situ* imaging of large batteries undergoing cycling could provide insight on volume and structural changes, which may cause battery degradation. This capability could also be used for *ex situ* analysis of shorted or abused cells. The system could be used to aid in studies involving cells constructed with internal instrumentation or those with a triggered internal short.

iii. Systems beyond Li-ion: The large number of useful electrode materials currently in use distinguishes Li-ion batteries from previous battery systems (e.g., lead-acid). While considerable progress is expected in the next few years in finding new materials that show high energy, long life, and thermal stability, a need exists to investigate systems that go beyond the framework of Li-ion so as to enable a tremendous increase in energy density. These include systems like zinc/air, lithium/air, and lithium/sulfur that could be used in vehicle applications and redox flow cells that would enable low cost and long life grid-scale storage.

While all of these systems have been the focus of extensive battery R&D at one time or the other, some fundamental issues have prevented their commercialization. For example, Li-metal-based systems have suffered from the inability to protect the interface between the Li metal and the electrolyte. Over the last few years, increasing evidence shows that single-ion conducting glasses

can protect metal electrodes. However the conductivity of these glasses is poor, and they are susceptible to cracking. We propose an effort to bring together ceramicists, polymer chemists, and electrochemists to design new coatings that will protect the Li. Progress in this area will also enable the use of a different anolyte and catholyte, each with voltage stability in the relevant region, with a single-ion conducting glass between them, thereby providing a way to enable higher-energy, longer-life batteries. A second focus area will be enhancing the rate of the oxygen reduction reaction in nonaqueous media. Enhancing the catalysis of this reaction will enable the use of air cathodes in lithium/air cells, a system that promises energy densities an order of magnitude greater than the present state of the art.

In the area of electrochemical energy technologies for use with renewable sources, a roadmap will be developed, which will consider alternative technologies and investigate the most valuable dual use technologies. The Electricity Storage Association has analyzed the relative capital costs associated with installing stationary energy storage systems of various types (<http://www.electricitystorage.org/pubs/2008/NewESACcharts2008v01.pdf>). These data show that, from a cost perspective, some of the most promising advanced battery technologies are:

- Some of the lowest cost Li-ion battery technologies
- High temperature battery technologies (e.g., Na/S and Na/Metal Chloride)
- Flow battery technologies (e.g., Zn/Br₂ and redox systems).

These technologies will be investigated for application in both automotive and stationary applications to identify research topics that will benefit both fields.

(3) Perform Fundamental Energy Storage R&D (to be provided by BES)

(4) Provide Testing and Analysis Support

Accurate testing support will be critical to the success of many of the other activities in this collaborative. R&D teams and the domestic manufacturing teams will be supported by testing facilities. Both the R&D ESRAC and the Manufacturing ESRAC will require accurate test data, focused analysis, modeling, and timely reporting to support decision points within the R&D team projects as well as prototype device testing support for the manufacturing teams. Existing test facilities and diagnostic testing capabilities within the national laboratories will be expanded, and new testing capabilities will be created to accommodate the anticipated level of support that will be required to execute this collaborative. Testing support will be available to the enhanced R&D area, the advanced battery development area, and the domestic manufacturing component. The following paragraphs provide sample testing and analysis activities.

Performance and life testing: Use testing and analysis techniques to understand cell discharge and charge performance during aging, and provide this data to diagnostics teams to understand the associated degradation mechanisms. DOE has established a large number of standard test procedures to characterize high power and high energy cells during HEV and PHEV-like operation. These procedures will be applied to existing and emerging energy storage technologies and will be continually monitored and improved as new stress factors are identified.

Abuse tolerance testing: Abuse tolerance remains a critical requirement for automotive batteries. Abuse tolerance testing will concentrate on both cell level and battery level controls. New diagnostic approaches may include *in situ* testing of internal short circuits, which has recently begun at Sandia National Laboratory. An internal short, believed to be caused by manufacturing defects, is the most difficult abusive event to predict and mitigate. It has been challenging to devise test methods that simulate an internal short in a realistic manner. Therefore, a new test method will be developed. This work needs to be investigated through diagnostic testing processes at national laboratories to identify the most appropriate materials and activation mechanisms. Once established, a standard test procedure could be adopted by testing institutions to evaluate the tolerance of various cell design and chemistries to internal shorts.

Diagnostic testing: Diagnostic testing and design of experiment are indispensable tools needed to support the exploratory and applied research component. This task will use testing and analysis techniques to understand cell aging and the associated degradation mechanisms. Supporting this testing will be various data analysis techniques, e.g., temperature sensitivity adjustments, lumped parameter modeling and Electrochemical Impedance Spectroscopy (EIS), cyclic voltammetry (CV), equivalent circuit modeling, multiple sigmoid model (MSM), and chemical kinetics rate expressions. The approach is based on two basic parts: (1) focused experiments or test conditions that target specific issues toward mechanistic-level knowledge of device performance and (2) a self-consistent theoretical and mathematical framework that enables intelligent data analysis and modeling.

In-vehicle battery testing: The EERE Advanced Vehicle Testing Activity will receive vehicle size systems to integrate into mule vehicles for laboratory and road testing of experimental designs still under development.

VI. Education and Outreach

The promise of HEV and PHEV technologies has fueled significant interest in both technologies, within the U.S. government, in industry, and throughout the general public. A tremendous amount of information is currently available about both technologies. However, the public, battery manufacturers, congressional staff, and others are keenly interested in DOE's current and planned activities in PHEV battery research. Therefore the NBC teams will develop and maintain a series of fact sheets and a DOE internet page to provide: (a) one-stop information shopping regarding current PHEV activities at the national laboratories, (b) DOE funding opportunities and current state-of-the-art battery performance based on independent performance, and (c) abuse testing being carried out at the national laboratories. In addition, this effort will regularly submit press releases through the DOE press office to inform the public about recent advances and new awards within the energy storage R&D area.

In addition to this traditional education and outreach function, NBC management will implement a focused program to help train or retrain U.S. workers for battery production and materials supply factory positions. These efforts will be cost shared with industry and will be essential to ensuring that U.S. developers have access to the appropriate number of well trained staff.

VII. Timeline and Milestones

The NBC is scheduled as a 6- to 8-year program. Major tasks and the associated timeline are shown in Figure 8. The domestic battery facilities construction and validation activities will begin nearly immediately. A number of near-market-ready technologies could be profitably produced domestically with a modest combination of customer demand and financial assistance to aid in building and qualifying the manufacturing facilities (e.g., the Li-ion technology that is being produced in France by Johnson Controls-Saft for Mercedes Benz and BMW).

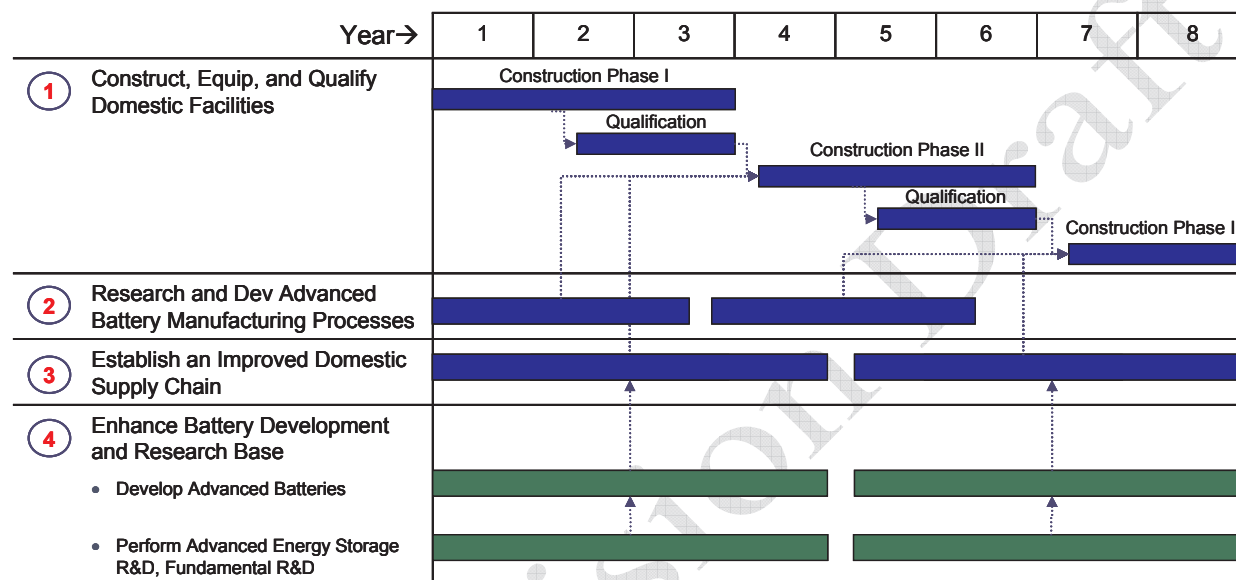


Figure 8. Major tasks, timeline, and task interactions in the NBC.

Some of the major milestones and deliverables planned for this effort are shown in Table 2.

Table 2. Major milestones and deliverables

Program Year	Milestone #	Item
Year 1	0	Form NBC program management office, and Energy Storage Research and Commercialization Centers (ESRACs)
	1	Issue initial domestic battery facility modification and construction Request for Proposal (RFP)
	2	Issue RFP for advanced battery design and development
	3	Issue RFP for battery R&D centers
Year 2	4	Issue RFP for domestic battery material supplier and equipment manufacturing
	5	Issue RFP for battery manufacturing technology development
	6	Open DOE national laboratory battery prototype manufacturing facilities
Year 3	7	Begin production qualification and validation of initial battery manufacturing facilities
	8	Issue 2 nd RFP for advanced battery design and development
Year 4	9	Issue 2 nd RFP for domestic battery material supplier and equipment manufacturing

Program Year	Milestone #	Item
	10	Issue 2 nd RFP for domestic battery facility modification and construction
	11	Down select and transfer most promising high energy battery couples to battery developers
Year 5	12	Issue 3 rd RFP for advanced battery design and development utilizing most promising high energy battery couples to battery developers
	13	Issue 2 nd RFP for battery manufacturing technology development
	14	Perform production qualification and validation of 2 nd round battery manufacturing facilities
	15	Next generation electrochemistry R&D
Year 7	16	Issue 4 th RFP for advanced battery design and development using most promising high energy battery couples to battery developers
	17	Issue 3 rd RFP for domestic battery facility modification and construction
Year 9	18	Perform production qualification and validation of 3 rd round battery manufacturing facilities