RANGE Program Overview

B. PROGRAM OVERVIEW

This program seeks to fund the development of transformational electrochemical energy storage technologies that will accelerate widespread electric vehicle adoption by dramatically improving their driving range, cost, and reliability. To achieve this long-term objective, this program aims to maximize specific energy and minimize cost of energy storage systems at the *vehicle* level. Central to this system-level approach is the use of *robust design* principles for energy storage systems. *Robust design* is defined as electrochemical energy storage chemistries and/or architectures (i.e. physical designs) that avoid thermal runaway and are immune to catastrophic failure regardless of manufacturing quality or abuse conditions. In addition, this program seeks *multifunctional energy storage designs* that use these robust storage systems to simultaneously serve other functions on a vehicle (for example, in the frame, body, and/or crumple zone), thus further reducing an energy storage system's effective weight when normalized to the entire electric vehicle weight. It is anticipated that the core technologies developed under this program will advance all categories of electrified vehicles (hybrid, plug-in hybrid, extended-range electric, and all-electric vehicles); however, the primary focus of this program is on all-electric vehicles, referred to hereafter as electric vehicles (EVs).

1. Background

Benefits of Electric Vehicles

The widespread adoption of electric vehicles can substantially reduce U.S. oil imports, mitigate greenhouse gas (GHG) emissions, and increase energy efficiency of transportation. The transportation sector is the single greatest source of U.S. dependence on imported oil. In 2010, 94% of U.S. transportation energy came from petroleum, nearly half of which came from foreign sources.[1] In terms of economic impact, petroleum imports represented nearly 41% of the $646 billion U.S. trade deficit in 2010.[2]

The transportation sector also represents about 27% of all U.S. greenhouse gas emissions.[3] However, even with today's U.S. electric power generation mix of fossil, nuclear, and renewable energy sources, it is estimated that on a well-to-wheel basis an all-electric vehicle will generate 25% less GHG emissions than a conventional gasoline powered vehicle,[4] with even lower emissions predicted with increased penetration of renewable energy sources. For comparison, models show that when driving EVs charged from today's electric grid, about 45% of Americans would reduce their GHG emissions compared to driving a 50 mpg Toyota Prius. As more renewable energy is installed, these models show that, by 2025, nearly 70% of the population would reduce their GHG emissions by driving EVs.[5]

Finally, electric vehicles have the promise to greatly improve transportation energy efficiency. On a well-to-wheel basis, the all-electric Tesla Roaster charged with electricity generated from natural gas has an efficiency of 1.14 km/MJ; nearly twice as efficient as a Toyota Prius hybrid (0.56 km/MJ) and four times more efficient than a typical gasoline-powered car, such as the Toyota Camry (0.28 km/MJ). [6]

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[1] U.S. Energy Information Administration. *Annual Energy Review 2010*. 19 Oct 2011.

[2] U.S. Census Bureau. Foreign Trade Statistics, 2011. http://www.census.gov/foreign-trade/index.html

[3] U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2010*. 2012.

[4] A. Elgowainy, et al. Argonne National Laboratory. *Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles*. Report No. ANL/ESD/09-2. Feb 2009.

[5] Union of Concerned Scientists, *State of Charge: Electric Vehicles' Global Warming Emissions and Fuel-Cost Savings Across the United States, Update June 2012*, http://www.ucsusa.org/clean_vehicles/smart-transportation-solutions/advanced-vehicle-technologies/electric-cars/emissions-and-charging-costs-electric-cars.html, (February 2013).

[6] M. Eberhard and M. Tarpenning. *The 21st Century Electric Car*. Tesla Motors. 6 Oct 2006.

Barriers to Electric Vehicle Adoption

Despite a compelling national imperative, electric vehicles have achieved very little market penetration in the U.S., with EV sales representing only 0.1% of the 14 million U.S. vehicles sold in 2012.[7] This may, in part, be explained by the high initial purchase cost of EVs relative to gasoline-powered vehicles. For example, when comparing an 2012 all-electric, 100 mile range Nissan Leaf ($28,550) to a gasoline-powered, 300 mile range Nissan Versa ($19,210) at a gasoline price of 4 $/gallon, the payback period for the average consumer is more than 7 years even after accounting for government subsidies.[8]

The incremental cost of electric vehicles, vs. internal combustion engines (ICE) vehicles, is dominated by the energy storage system with current EV grade lithium-ion battery pack costs of 400-800 $/kWh.[9] As a consequence, the EV price is directly correlated with battery pack size and therefore vehicle range (Figure 1). By restricting the EV range to 100 miles and minimizing the required battery pack size, EV manufacturers can market and sell these electric vehicles at a price that is acceptable to a small segment of the population. However, these low energy capacity EVs do not meet the 300-mile driving range that a majority of U.S. consumers have come to expect in vehicles.[10] On the other hand, EV manufacturers such as Tesla Motors produce a vehicle with > 250 mile range, but at a price significantly higher than average gasoline powered vehicles.[11] By contrast, ICE vehicles show no clear correlation between price and range, as shown in Figure 1. This is largely because, unlike batteries, the size of the fuel tank and the amount of fuel contribute little to vehicle price or weight.

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[7] Electric Drive Transportation Association (EDTA), *Electric Drive Vehicle Sales Figures (U.S. Market) – EV Sales*, http://www.electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952, (February 2013).

[8] M. Krebs, *Will Higher Gas Prices Boost Hybrid, EV Sales?,* Edmunds.com, 28 February 2012, http://www.edmunds.com/industry-center/analysis/will-higher-gas-prices-boost-hybrid-ev-sales.html.

[9] S. Sun. Energy Smart Technologies – Energy – Research Notes. *Bloomberg New Energy Finance*, December 17, 2012

[10] C. Giffi, J. Vitale Jr., M. Drew, Y. Kuboshima, & M. Sase, *Unplugged: Electric Vehicle Realities Versus Consumer Expectations*, 21 September 2011, http://www.deloitte.com/assets/Dcom-Global/Local%20Assets/Documents/Manufacturing/dttl_Unplugged_Global%20EV_09_21_11.pdf.

[11] TESLA, *Model S*, http://www.teslamotors.com/models/options, (February 2013).

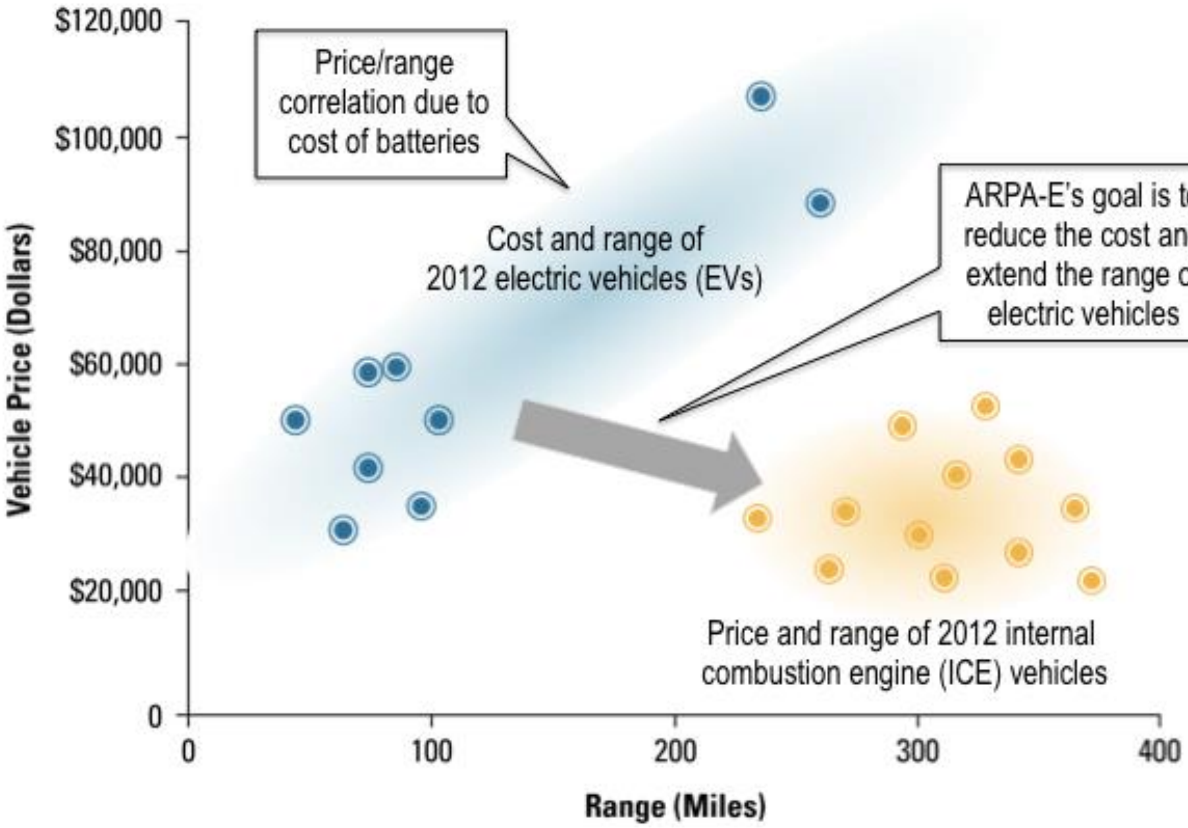

Figure 1: U.S. electric vehicle price as a function of range in 2012. The correlation between price and range is primarily due to the high cost of batteries. In order to reach near vehicle price and range parity with gasoline-powered vehicles, a dramatic cost reduction and increase in range is needed.

Current Research Programs

Major research and development efforts have been devoted to increasing the specific energy of lithium-ion battery cells in order to extend the range of EVs and to reduce their cost (assuming the cost of materials and manufacturing do not significantly vary for higher specific energy systems). For long range EVs, battery pack weight is a significant portion of the vehicle weight (1/4 to 1/3).[12] A recent study showed that for every 10% vehicle weight reduction, there is about a 5% reduction in energy consumption.[13]

The U.S. Department of Energy (DOE) has actively pursued higher specific energy density battery chemistries for over a decade. For example, the Vehicle Technology Program in the Office of Energy Efficiency and Renewable Energy (EERE) has sponsored a broad portfolio in lithium-ion battery technologies, ranging from electrode and electrolyte materials to manufacturing processes, diagnostics, testing and analysis.[14] In 2010, ARPA-E's BEEST (Battery for Electric Energy Storage for Transportation) program began funding the development of even higher specific energy chemistries, such as lithium-sulfur and lithium-air batteries.[15] More recently, DOE launched the "EV Everywhere" initiative aimed at dramatically reducing the cost of EVs through improved batteries, electric drive components, and vehicle lightweighting.[16]

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[12] TESLA, *Increasing Energy Density Means Increasing Range*, http://www.teslamotors.com/roadster/technology/battery, (February 2013).The Tesla Roadster has a curb weight of 2723 lbs with a battery weight of 990 lbs.

[13] C. Shutte. *Lightweighting EVs*. Presentation at EV Everywhere Workshop, Washington DC, 2012.

[14] Vehicle Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. *2012 Annual Merit Review, Vehicle Technologies Program*. Results Report, Oct 2012.

[15] ARPA-E, *Batteries for Electrical Energy Storage in Transportation*, http://arpa-e.energy.gov/?q=arpa-e-programs/beest, (February 2013).

[16] US DOE EERE, *EV Everywhere Grand Challenge*, http://www1.eere.energy.gov/vehiclesandfuels/electric_vehicles/index.html, (February 2013).

In addition to efforts focused on cell-level innovations, battery pack-level research has also received increasing attention. In 2012, ARPA-E initiated the AMPED (Advanced Management and Protection for Energy Storage Devices) program,[17] which focuses on improving lithium-ion battery cell utilization and state-of-health prognosis by developing advanced controls, models and sensors. If successful, the AMPED program will improve the useable specific energy of lithium-ion battery packs without changing its chemistry.

Program Challenge

Traditional research approaches to enhancing electric vehicle energy storage systems have focused primarily on increasing cell-level specific energy density; however, the cost and performance advantages of high specific energy cells are often offset by more demanding pack-level and system-level engineering requirements. In order to realize very high pack-level specific energies, one needs to maximize both the cell performance and the packing factor;[18] unfortunately, there is an inherent tradeoff between these two features. High specific energy batteries often employ high-voltage redox couples and flammable organic electrolytes. In these systems, the total combustible energy in a lithium-ion cell can be an order of magnitude greater than the stored electrochemical energy.[19] Out of concerns for thermal runaway, thermal and electric control and management systems are employed, but these reduce the packing factor. Moreover, higher specific energy cells often demand extensive mechanical protection to avoid intrusion and deformation. Consequently, packing factors tend to decrease as battery cell-level specific energy increases, resulting in additional vehicle-level structure and weight. In fact, it is common practice to design the battery pack as if it were a fuel tank (i.e., isolate the energy storage component from the rest of the vehicle) rather than as one component in a larger system. For example, the design of the Ford Focus EV employs an additional vehicle structure that surrounds the battery pack in order to avoid pack intrusion.[20] These additional protective structures significantly reduce the effective specific energy of the energy storage system. Despite these conservative system designs, several incidents of electric vehicle fires have raised concerns for consumers and illustrate the challenges of addressing abuse tolerances with *ad hoc* system-level engineering solutions.[21] Consequently, concerns over battery cell life and thermal runaway require thermal and mechanical protection that can lead to lithium-ion battery packs costing >80% more than the cells, while the specific energy decreases by more than 40%.[22,23]

High specific energy cells with flammable materials also suffer from increased materials and manufacturing costs resulting from limited robustness. The demanding high voltage environments of high specific energy electrode couples require the use of costly, ultra-pure electrolytes and electrode materials. In addition, highly precise and reproducible manufacturing processes are critical to minimize defects that can lead to cell failure. Both the material and manufacturing aspects contribute significantly to the high cost of lithium-ion batteries.[24] Such problems are also exceptionally relevant to the successful pursuit of a business strategy, as shown by the battery recalls.[25]

Program Approach

ARPA-E seeks alternative pathways to lower cost, longer range EVs that focus on energy storage systems with improved *vehicle-level* specific energy, rather than only cell or pack-level improvements. This approach requires the development of

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[17] ARPA-E, *View Programs*, http://arpa-e.energy.gov/?q=projects/view-programs, (February 2013).

[18] *Packing factor* = gravimetric or volumetric (*cell energy density* / *pack energy density*) x 100%

[19] J. Harmon, et al. *US FAA-Style Flammability Assessment of Lithium-Ion Battery with and Contained in Equipment (UN3481)*. Exponent, Inc. Report, Mar 2010.

[20] D. Gabrielli. Summary of Safety Related Vehicle Design Issues. Presentation. *3rd Annual Electric Vehicle Safety Standards Summit*. Detroit, MI. 2012.

[21] US DOT, *Chevron Bolt Battery Incident Overview Report*, January 2012, http://www-odi.nhtsa.dot.gov/acms/cs/jaxrs/download/doc/UCM399393/INRP-PE11037-49880.pdf.

[22] Element Energy Limited, Cost and performance of EV batteries, Final report for The Committee on Climate Change, 21 March 2012, http://hmccc.s3.amazonaws.com/IA&S/CCC%20battery%20cost_%20Element%20Energy%20report_March2012_Public.pdf.

[23] Wagner, et al, Electrochemistry and the Future of the Automobile, J. Phys. Chem. Lett., 1, 2204, 2010

[24] D. Howell. Battery Status and Cost Reduction Prospects. Presentation. *EV Everywhere Grand Challenge*. 26 Jul 2012.

[25] A. Hesseldahl, “More Sony Battery Recalls”, BusinessWeek, 28 September 2006, http://www.businessweek.com/stories/2006-09-28/more-sony-battery-recalls.

robust energy storage chemistries and architecture. Some examples include: the development of an electrochemical energy storage chemistry that utilizes non-combustible aqueous or solid state electrolytes; the use of a redox flow battery architecture that is inherently more robust due to the physical separation (storage) of its active components far from the cell electrodes; and the design of a mechanism that allows a battery to automatically fail in open circuit when placed under abuse conditions. Robust designs have the potential to transform EV design and create new pathways to dramatically lower cost by: 1) reducing the demands on system-level engineering and its associated weight and cost; 2) liberating the energy storage system from the need for vehicle impact protection, which allows the energy storage to be positioned anywhere on the vehicle, thereby freeing-up the EV design; and 3) enabling multiple functions, such as assisting vehicle crash energy management and carrying structural load.

Multifunctional energy storage designs help reduce the effective weight of an EV energy storage system. In Figure 2, the weight distribution of an EV powered by a traditional lithium-ion battery is compared to one powered by a robust, multifunctional battery. If the vehicle-level specific energy requirements are assumed to be the same, the reduction in protection/control overhead with the multifunctional battery relaxes the need for a high cell-level specific energy. This design freedom may allow the use of battery chemistries with lower theoretical specific energy that are not considered viable today. If these chemistries have inherently lower cost structures than lithium-ion batteries, a new set of EV energy storage technology solutions becomes possible.

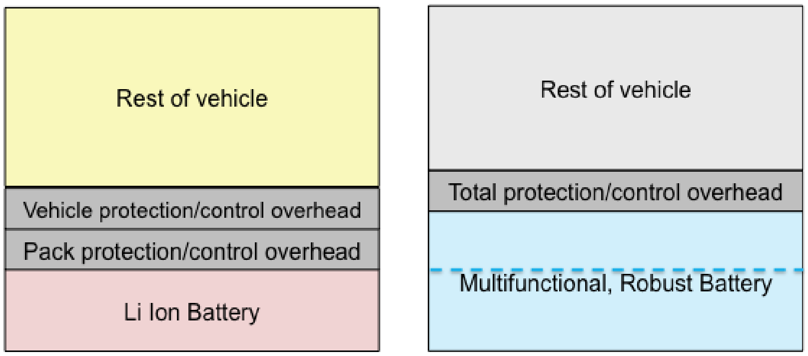

Figure 2: A schematic comparison of weight distribution of two EVs with the same vehicle level specific energy, or Wh/kg-vehicle. As compared to a future lithium-ion battery, a multifunctional, robust battery design reduces system overhead as well as the rest of the vehicle weight since the battery serves part of the vehicle function. Despite the great difference in battery weight, the two vehicles have the same Wh/kg-vehicle and range.

To connect performance and cost requirements for the robust battery systems with vehicle range and system costs, ARPA-E performed an analysis to set specific energy system and cost targets that would ultimately lead to electric vehicles at cost parity with ICE vehicles. Current performance requirements for lithium-ion batteries are usually defined at the pack level in industry technology development roadmaps such as those defined by USABC.[26] Analysis performed for this program shows that a cost to manufacture target of 100 $/kWh and a specific energy of 150 Wh/kg on a pack level should enable a long range EV (> 240 miles) with competitive vehicle purchase price (<$30,000).[27] For energy storage systems with multifunctional capabilities, these targets and metrics will still apply but require further clarification. We define a new metric termed "effective specific energy", which is explained in more detail in Section E. If the energy storage system reduces the need for a structural part, the weight of the structural part is subtracted from the storage system

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[26] United States Council for Automotive Research LLC, *News: Energy Storage System Goals*, http://www.uscar.org/guest/article_view.php?articles_id=85, (February 2013).

[27] ARPA-E estimated this range metric as follows: We set a price target of 125 $/mile of range for an EV design study since this metric best represents the vehicle selling price. One exemplary case is an EV that carries 60 kWh of useable energy, if the vehicle weighs 3,000 lbs (1,360 kg) and consumes energy at a rate of 250 Wh/mile, this vehicle will have a range of 240 miles. This energy consumption rate is comparable to that of the Tesla Roaster (227 Wh/mile for 2723 lbs of vehicle weight (see Ref. 13). Using a selling price of 125 $ per mile of range as a design criterion, we performed a quantitative tradeoff between the specific energy of the storage system and its cost. When battery specific energy decreases, the added weight will increase total vehicle weight. For every 10% increase in weight, a 6.5% decrease in range is assumed. A lower cost target thus allows a lower specific energy while maintaining the same selling price per mile of range. Our low cost target of 100 $/kWh for the battery pack enables the use of a moderate effective specific energy target of 150 Wh/kg, consuming 400 kg (29%) of the total weight of the vehicle.

weight. The difference is then used to calculate the specific energy. This new metric thus embodies the impact of synergistic interplay between energy storage and vehicle structure. We note that vehicles of the same weights equipped with batteries of the same "effective specific energy" will have the same vehicle level specific energy. While a similar cost benefit is expected, the magnitude varies greatly (on the order of > 100%) with the actual vehicle platform. Internal ARPA-E analysis shows a cost benefit of > 25 $/kWh due to weight reductions by employing multifunctional design.[28] Consequently, ARPA-E expects that a cost target of 125 $/kWh for a multifunctional energy storage system will enable achievement of the program goals of a >240 mile range at <$30,000 vehicle price.

C. PROGRAM OBJECTIVES

Consistent with ARPA-E's mission, this funding opportunity announcement (FOA) seeks to foster novel approaches in energy storage systems for electric vehicles. The program goal is to enable a 3X increase in electric vehicle range (from ~80 to ~240 miles per charge) with a simultaneous price reduction of > 1/3 (to ~ $30,000). If successful, these vehicles will provide near cost and range parity to gasoline-powered ICE vehicles.

In order to support the long-term goal, the first objective of this program is to fund the development of low-cost, rechargeable energy storage chemistries and architectures with robust designs. Aqueous or other low-cost inorganic electrolyte based systems and novel cell geometries are of particular interest, as are flow battery architectures employing liquid or slurry-based reactants that enable physical isolation of active materials.

The second objective of this program is to fund the development of multifunctional energy storage systems. Note that robust design characteristics may enable energy storage systems to simultaneously serve other functions on an electric vehicle. Energy storage systems which absorb impulse energy during a vehicle crash and/or which carry mechanical load are of particular interest. Both of these functions are expected to extend the EV's operating range by reducing the vehicle's overall weight.

D. TECHNICAL CATEGORIES OF INTEREST

This program is focused on supporting chemistry and system concepts in energy storage with robust designs in one or both of the following categories:

- **CATEGORY 1: Robust energy storage chemistries and architectures**
- **CATEGORY 2: Multifunctional energy storage designs**

While ARPA-E will consider proposals addressing these two separate categories, ARPA-E expects that the solution having the highest potential to meet the performance targets is a combination in which both chemistry and architecture together provide a multifunctional role while preventing thermal runaway. The goal is for this combination to bring the most

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[28] ARPA-E calculation: this is an estimate; it is the total cost savings (material and labor) due to elimination/consolidation of components normalized to the energy stored in the battery pack (see for example, Sven Ginsberg, Crash Deformable Battery Concept for Electric Vehicles, Aachen Body Engineering Days, September 22, 2012). An exemplary case is a vehicle with a battery pack capable of absorbing mechanical impact. Savings estimated include: 1) the reduction of materials and labor cost due to the elimination of protective structures; and 2) additional cost savings due to avoidance of the weight compounding effect if the protective structures were present, e.g., the need to use more expensive light weight materials in order to maintain overall vehicle weight.

impact in terms of weight and cost savings. *As a result, proposed solutions addressing both categories will be given preferred consideration.*

For Category 1, ARPA-E has interest in funding energy storage chemistries and architectures with robust design features. Examples of technical approaches include but are not limited to:

- High specific energy aqueous batteries. Areas of particular interest are approaches to novel high specific energy cathode/anode redox couples; materials and device designs for long life metal-air systems; ultrahigh capacity negative electrode materials to replace La-Ni alloys in nickel metal hydride batteries; and organic and inorganic redox couples, including their hybrids.
- Ceramic and other solid electrolyte batteries. Areas of particular interests are high conductivity inorganic electrolytes for lithium and other alkaline metal ion systems; and solid state and hybrid battery designs and low cost manufacturing processes.
- Other batteries completely without or with negligible combustible or flammable materials.
- Materials and architectures that eliminate the possibility of thermal runaway;
- Robust design architectures. Examples include flow cells and electrically rechargeable fuel cells, fail open circuited designs, non-propagating system architectures, and designs resulting in reductions in individual storage unit sizes and energy contents.
- Hybridization of different energy storage chemistries and architectures to offer improved robustness including mechanical abuse tolerance.

For Category 2, ARPA-E is looking for innovative designs that optimally utilize energy storage systems to contribute to vehicle structural performance. Examples of technical approaches include but are not limited to:

- Energy storage systems that assist vehicle impact energy management. Areas of particular interest are material, cell, pack, and system designs that act synergistically with the rest of the vehicle structure to manage mechanical impact. Energy absorption mechanisms may include deformation, disintegration, and disengagement by design.
- Energy storage systems that act as structural members. In this case, the energy storage system may directly replace other structural members of the vehicle in the load path.
- Energy storage systems that serve other vehicle functions not listed above.

The ideal Project Team will have engineering/scientific expertise in every aspect of the system conceptualization and a good understanding of material properties, energy storage systems, and vehicle design. This teaming arrangement is especially important for projects focused on Category 2 since any claim of multifunctional benefit requires a solid understanding of vehicle structure and design requirements. ARPA-E does not mandate the participation from automotive original equipment manufacturers (OEMs), rather, the team needs to have the necessary expertise in automotive systems.

E. TECHNICAL PERFORMANCE TARGETS

The final research objective for projects funded under this FOA is a fully integrated energy storage unit with energy content of 1 kWh or greater. This minimal size is chosen so that results from the robustness tests as defined below can be readily used to predict the robustness of full size EV energy storage systems. However, ARPA-E will consider innovative partial solutions under the Seedling funding category as described in more detail at the end of this Section.

PRIMARY TECHNICAL TARGETS

ID	Parameter	Primary targets
1.1	Cost to manufacture	< 100 - 125 $/kWh
1.2	Effective specific energy	> 150 Wh/kg
1.3	Effective energy Density	> 230 Wh/L
1.4	Robustness	Meet primary targets detailed below

METRIC DESCRIPTIONS – PRIMARY TECHNICAL TARGETS

1. Cost to manufacture. To attain near cost parity between the EV and a gasoline powered vehicle, the cost to manufacture the energy storage system needs to be less than 125 $/kWh if they are multifunctional and 100 $/kWh if they are not. This cost includes the cost of materials as well as the cost of labor and facilities for manufacturing. It does not include profits for either the energy storage system maker or the automotive OEM.

   Applicants should provide sufficient evidence to justify cost targets. Additional justification for approaches that will reduce manufacturing costs should be elaborated. A credible path to reach this metric is required.

   While not mandatory, applicants are encouraged to use an open source battery cost model such as the BatPac model developed by Argonne National Laboratory; visit http://www.cse.anl.gov/batpac/about.html for more details. When using this or a similar model, applicants are required to highlight the major assumptions made in their calculation and provide a justification for those assumptions.

2. Effective specific energy. The specific energy is calculated using the total usable energy measured at a C/3 rate divided by the mass of the whole energy storage system, including any control, thermal management system (hardware and fluid if used), and enclosure. A C/3 rate is defined as a current level to discharge the battery in 3 hours. For proposals claiming multifunctional use of the energy storage system, the mass reduction in other parts of the vehicle can be subtracted from the weight of the energy storage system before the specific energy is calculated. In order to justify the subtraction, applicants are required to present a vehicle model, including simulations for crashworthiness, using computer aided engineering design tools. While ARPA-E does not specify a vehicle platform, such vehicle is envisioned to be a mid-size, 5 passenger car. Simulations should show that the vehicle would pass all relevant NHSTA vehicle safety regulations in particular as related to crash tests. Recommended tests include: Side impact: NHTSA FMVSS214 standard, 33.5mph, 27° moving deformable barrier; Frontal impact: NHTSA FMVSS208 standard, frontal crash test, 35 mph, flat barrier, 0 degree offset; Rear impact: NHTSA FMVSS301 standard, 50mph 70% offset, moving deformable barrier. Applicants are encouraged to compare the simulation results with those from a gasoline-powered vehicle of similar size and weight. Alternatively, if an energy storage system is proposed as a direct replacement of a structural element, the system has to demonstrate comparable mechanical properties.

3. Effective energy density. Energy density is defined as the total usable energy measured at C/3 rate divided by the volume of the energy storage system. The dimensions of the system are defined by the outer boundaries. If other vehicle components are situated inside this volume, that portion of the volume can be subtracted. If the energy storage system serves as multifunctional units in a vehicle, the volume it replaces can be subtracted in order to calculate the effective energy density.

4. Robustness. The primary criteria for the energy storage system is to pass the crush test as follows: experience a crush test to 50% of original dimension or at a 1 g- force of 1000 times of battery mass without maximum temperature on any point of the inner or outer surfaces reaching either the flash point of any volatile component (both original and generated during operation) or the melting point of any solid component. This target is essentially to eliminate the

possibility of thermal runaway and vehicle fire. Applicants are required to perform necessary analysis to show why their choices of chemistry and system design will enable meeting these criteria. Applicants are encouraged to acquire experimental data by performing the prescribed test. ARPA-E, however, expects to require performers to submit sample systems for third party testing and validation. ARPA-E strongly advocates robust design approaches to energy storage systems. In light of the potential of using these systems to serve multiple vehicle functions where mechanical abuse is likely to take place, it is critically important to ensure high degree of abuse tolerance.

SECONDARY TECHNICAL TARGETS

ID	Parameter	Secondary targets
2.1	Cycle life at 80% depth of discharge (DOD)	> 1000
2.2	Calendar life	> 10 years
2.3	Effective specific Power – Discharge, 80% DOD/30 s	> 300 W/kg
2.4	Operating temperature	-30^{o}C -
2.5	Secondary robustness requirements	Meet requirements below

METRICS DESCRIPTION-SECONDARY TECHNICAL TARGETS

1. Cycle life at 80% DOD. Cycle life of > 1000 is required to ensure that the energy storage system will last the life of the vehicle. During this program, the applicant should demonstrate a lifetime of greater than 500 cycles with more than 85% of initial capacity. The long-term goal is 1,000 cycles. Given the short duration of ARPA-E projects (< 3 years), the time required to test 1,000 cycles may not be practical. However, applicants should provide a well-justified description of how their technology will achieve the long-term cycle life goal based on testing, analysis, and modeling.
2. Calendar life. A calendar life of > 10 years is required to ensure that the energy storage system will last the lifetime of the vehicle. This is especially important for multifunctional designs where replacement might be difficult. Given the short duration of ARPA-E projects, it is not possible to actually measure any significant portion of the calendar life. Applicants are required to provide analysis/modeling in combination with any laboratory testing data to justify why a 10-year life might be possible. Variable temperature studies that indicate sensitivity are encouraged.
3. Effective specific power. The energy storage system is required to deliver power capabilities at 300 W/kg for 30 s when discharged to 80% of DOD. In consistency with the definition of effective specific energy, multifunctional systems are allowed to subtract the weight of the vehicle part that they replace before the calculation is made.
4. Operating temperature. The energy storage system is required to be operational at temperatures > -30^{o}C. While a higher temperature bound is not defined here, the energy storage system should not impose additional thermal management burdens on the rest of the vehicle systems. The outer surface of the energy storage system should not exceed 52^{o}C.[25]
5. Secondary robustness requirements. While ARPA-E believes that meeting the primary target will effectively address thermal runaway caused by mechanical abuse, the applicants are required to consult the published USABC mechanical abuse tests and show through analysis and testing how the proposed systems will meet or

exceed the requirements.[29] ARPA-E reserves the right to arrange third party validation, in addition to the tests being done by the performance teams themselves

Seedling/Proof of Concept funding category for novel partial solutions

ARPA-E recognizes that there may be new high-impact ideas related to the aforementioned areas of interest that are exploratory in nature and may not yet be mature enough to meet the scale and degree of validation required in the primary targets above. For such unproven and yet promising ideas, ARPA-E seeks smaller seedling applications to conduct experiments to achieve a proof-of-concept. In this case, the proof-of-concept experiments must be designed in a way that the results obtained clearly indicate paths to approach full system applicability. For example, ARPA-E recognizes the challenge of developing an unproven, brand new chemistry to a 1 kWh system demonstration in less than 3 years. ARPA-E will consider particularly promising ideas that can achieve proof-of-concept in a seedling effort. See Section II.A below for further details.

F. APPLICATIONS SPECIFICALLY NOT OF INTEREST

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in Section I.E of the FOA, including but not limited to:
    - Incremental improvements to lithium-ion battery components that have little potential to reduce system complexity, weight, and cost
    - Approaches that employ higher specific energy cells coupled with a reduction in packing factor
    - Incremental improvements to mechanical protection structures for energy storage systems
    - Sensing, monitoring, and modeling of lithium-ion battery cells and systems that improve diagnosis but do not reduce system cost and improve crash worthiness
    - Energy storage technologies with significantly lower performance than lithium-ion batteries at a vehicle level, unless they are offered as part of a system solution that meet program metrics
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.
- Applications for basic research aimed at discovery and fundamental knowledge generation.
- Applications for large-scale demonstration projects of existing technologies.
- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.

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[29] United States Council for Automotive Research LLC, *News: USABC Manuals*, http://www.uscar.org/guest/article_view.php?articles_id=86, (February 2013).

Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).

Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy (e.g. Office of Energy Efficiency and Renewable Energy, Vehicle Technology Program and the Office of Science, Basic Energy Sciences program including the Energy Frontier Research Centers and the Batteries and Energy Storage Energy Innovation Hub).