CHANGING WHAT'S POSSIBLE

BEEST Program Overview

B.1. BACKGROUND

Petroleum consumption in the United States transportation sector represents the dominant source of U.S. foreign energy dependence and a major source of U.S. greenhouse gas emissions. In 2008, the U.S. consumed 19.5 million barrels of petroleum per day, 57% of which was imported from foreign sources. The transportation sector dominates U.S. petroleum consumption and petroleum consumption dominates the U.S. transportation sector, with nearly 70% of U.S. petroleum consumption occurring in the transportation sector and 95% of U.S. transportation energy provided by petroleum. Light-duty vehicles represent the dominant source of U.S petroleum usage, representing more than 60% of all petroleum usage in the transportation sector.[1] The petroleum-powered U.S. transportation sector is also a dominant contributor to U.S. greenhouse gas emissions, accounting for ~30% of U.S. CO_2 emissions.[2]

The development and widespread deployment of cost-effective electrified light-duty vehicles represents a tremendous opportunity for dramatic reductions in U.S. oil imports and greenhouse gas emissions by shifting the U.S. transportation energy supply from petroleum to the domestically powered U.S. electric grid. Plug-in hybrid (PHEV) and all-electric electric vehicles (EV) hold the potential to completely eliminate oil usage in the U.S. transportation sector. Electric vehicles powered by the current ~50% coal powered U.S. power generation mix can also reduce CO_2 emissions per mile by ~34% relative to current internal combustion engine based vehicles, with avoided CO_2 emissions increasing further as the U.S. electric grid continues to decarbonize going forward.[3]

Electric vehicles have the further advantage of offering significantly reduced fuel prices relative to petroleum powered vehicles. Assuming $3.00/gallon gasoline and 10¢/kWh electricity prices, fuel savings of up to 10¢/mile can be realized in electric vehicles.[4] However, the widespread deployment of electric vehicles has been prevented to date by their limited range and high upfront capital costs due to the limitations of currently available battery technologies. Currently available high performance Lithium-ion battery technologies are limited to system level energy densities of ~100-120 Wh/kg, costs of $800-$1200/kWh, and short cycle life, resulting in unacceptably short driving range for the vast majority of consumers and un-economically high lifetime costs for electric vehicles.

The U.S. Department of Energy's Office of Vehicle Technologies (OVT) and the United States Advanced Battery Consortium (USABC) have provided critical support for the development of advanced Lithium-ion batteries to enable widespread cost-effective deployment of hybrid electric vehicles (HEVs), with a 2010 goal to enable high performance Lithium-ion HEV power batteries at $20/kW. With this impressive goal nearly accomplished, these U.S. battery R&D funding organizations are now turning their focus toward their 2014 goal of increasing the energy density and decreasing the cost of Lithium-ion batteries for PHEVs to enable battery systems with energy densities of 140 Wh/kg to provide 40 miles of all electric range (PHEV-40) at a total battery cost of $3,400 or less (<$300/kWh). With this ambitious 6 year PHEV-40 program, the DOE OVT and USABC are pushing up against the fundamental energy density limits of traditional Lithium-ion based batteries.

There are strong doubts in the battery community as to whether the energy density of Lithium-ion batteries will be able to be pushed to the 200+ Wh/kg system level energy densities required for widespread deployment of all-electric vehicles. Furthermore, with current HEV battery production and Lithium-ion battery production dominated by Japan, South Korea, and to a growing extent China, there are doubts as to whether traditional Lithium-ion based battery production for electrified vehicles offers an opportunity for the U.S. to assert domestic technology and manufacturing leadership within the context of the existing Lithium-ion based battery technology platform. For these reasons, and given the strong existing focus of the DOE Office of Vehicle Technologies and the USABC on Lithium-ion battery technologies, ARPA-E has strong

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[1] Department of Energy, Energy Administration Agency, http://www.eia.doe.gov.
[2] "Inventory of Greenhouse Gas Emissions and Sinks: 1990-2007", Environmental Protection Agency, Report #: EPA 430-R-09-004.
[3] ARPA-E internal analysis. Assumptions: 485 g CO_2/mile baseline, 698 g CO_2/kWh current U.S. electric grid carbon intensity.
[4] ARPA-E internal analysis. Assumptions: $3.00/gallon gasoline, 25 mpg internal combustion engine vehicle, 10c/kWh, 4 miles/kWh electric vehicle.

interest in supporting the development of new high energy, low cost battery technology approaches beyond traditional Lithium-ion batteries.

In this Funding Opportunity Announcement (FOA), ARPA-E seeks to develop a new generation of ultra-high energy density, low-cost battery technologies capable of providing sufficient performance and cost to enable widespread deployment of long all-electric range PHEVs (PHEV-100+) and all electric EVs and with high potential to provide an opportunity for the U.S. to gain technology and manufacturing leadership in the emerging EV battery market. While ARPA-E's interest is in batteries for both long range PHEVs and EVs, the ambitious targets for this FOA are largely based upon the long term EV battery goals that the USABC has determined must be met for widespread deployment of EVs.[5] These targets include a system level specific energy density of 200 Wh/kg, volumetric energy density of 300 Wh/liter, cycle life of 1000, and a cost of $250/kWh.[6] As discussed below, these ambitious energy density and cost goals represent the greatest challenge for future battery development and thus will be the primary focus of this FOA. ARPA-E's objective is to fund high risk, high reward research efforts that, if successful, will have a transformational impact on the rate and scale of deployment of long range PHEVs and all electric EVs and provide U.S. technology and manufacturing leadership in advanced batteries for electrified vehicles.

B.2.OBJECTIVES

This FOA is primarily focused on the development of advanced battery chemistries, architectures, and manufacturing processes with the potential to provide EV battery system level energy densities exceeding 200 Wh/kg (mass density) and 300 Wh/liter (volumetric density) at system level costs of $250/kWh or below. The ability for proposed battery technologies to achieve system level target metrics on a number of other key performance parameters (detailed below) is of significant, but secondary, importance, as it is ARPA-E's belief that the required ambitious energy density and cost metrics for widespread adoption of EVs represent the most significant challenges and emerging technology opportunities facing battery technology development for EV applications today.

Due to the strong focus of existing U.S. battery research and development programs (DOE OVT, USABC) on traditional spiral-wound and pouch-based Lithium-ion cell based systems consisting of carbon-based anodes and Lithium-intercalation based cathodes (including $LiCoO_2$ and lower cost variants – $Li(Ni,Co,Al)O_2$, $Li(Ni,Mn,Co)O_2$, $LiMn_2O_4$, $LiFePO_4$ and various derivative systems)), combined with the limited remaining potential for energy density improvements in traditional Lithium-ion intercalation based systems, ARPA-E's primary focus in this FOA is to support the development of novel battery storage technologies beyond carbon-based anode/Li-intercalation cathode systems. Furthermore, in order to enable U.S. manufacturing leadership in the next generation of high performance, low cost EV batteries, ARPA-E is particularly interested in supporting new battery technology approaches that are enabled by new architectures and manufacturing approaches that go beyond the current state-of-the-art slurry coating based process that is currently dominated by non-U.S. battery manufacturers.

B.3. AREAS OF INTEREST

Any technology able to meet or exceed the "Primary Technical Requirements" and to meet or exceed the majority of the "Secondary Technical Targets" stated below will be considered for award under this FOA. However, areas of particular interest for this FOA include, but are not limited to, the following:

- Metal-air battery approaches that address the low cycle life, low power density, and low round trip efficiency of current approaches; especially related to improvements in the bifunctional air cathode. All Metal-air battery

[5] "USABC Goals for Advanced Batteries for EVs", United States Advanced Battery Consortium (United States Council on Automotive Research), http://www.uscar.org

[6] Note: The long term USABC EV battery goal for battery system cost is $100/kWh. The $250/kWh goal here is an updated ARPA-E goal derived from ARPA-E's "Workshop on Electrical Energy Storage for Vehicles" on Nov 3, 2009 and is based on a higher gasoline price relative to that assumed when USABC goals were created in 1991. Average gasoline prices in 1991 were $1.10/gallon. Assuming $2.27/gallon current gasoline prices an updated cost metric of $250/kWh was determined.

chemistries are of interest. ARPA-E believes that particularly strong opportunities exist to borrow innovations from the fuel cell field to improve the bifunctional air cathode.

- Lithium-sulfur battery approaches that address the low cycle life and high self-discharge of existing state-of-the-art technology.
- Disruptive new Lithium-air battery concepts that have the potential to dramatically increase device level power density, cycle life, and round trip efficiency from their current low levels; with particular interest in advanced approaches for dramatically improving the performance and cycle life of the bifunctional air cathode. ARPA-E believes that particularly strong opportunities exist to borrow innovations from the fuel cell field to improve the bifunctional air cathode.
- Advanced batteries with novel Li-metal anode protection schemes.
- Non lithium based intercalation batteries.
- Advanced Lithium-ion based battery systems that greatly exceed the energy density potential of existing traditional Lithium-ion based systems, including displacement reaction cathodes and other advanced approaches.
- Other highly novel battery/electrical energy storage approaches with potential for very high energy density and low cost.
- Novel battery architectures, manufacturing processes, and packaging schemes.
- Advanced battery chemistries, architectures, and manufacturing processes that hold strong potential to enable the U.S. to gain leadership in EV battery technology development and manufacturing.

ARPA-E is not interested in funding projects with any of the following attributes:

- Incremental improvements in Lithium-ion batteries.
- Component innovations that are not validated through demonstration of device and/or system level performance demonstration.
- Technology areas that have already received significant support from the DOE Office of Vehicles (including its Batteries for Advanced Transportation Technologies (BATT) program) and the United States Automotive Battery Consortium. These funding programs have mainly focused on traditional and emerging Lithium-ion battery approaches to date.
- Technology areas with clear technology show stoppers in any of the Primary Technical Requirements or Secondary Technical Targets that are not addressed clearly by the applicant.

B.4.TECHNICAL REQUIREMENTS

B.4.1 Quantitative Technical Metrics

This FOA is focused around supporting battery technology research and development projects that are able to address the specific quantitative target performance and cost metrics described below. Proposed technology development plans must have well justified, realistic potential to meet or exceed the stated “Primary Technical Requirements” by the end of the period of performance of the proposed project in order to be considered for award. Proposed technologies will secondarily be evaluated against their well justified, realistic potential to approach the “Secondary Technical Targets” by the end of the period of performance of the proposed project. Proposed technologies will still be considered for award if they fall short of one or more of the Secondary Technical Targets below, but will be evaluated and compared to one another according to their ability to address these targets.

The general expectation is that applicants will be proposing to develop and demonstrate technologies at the cell level. Relevant cell and system level metrics are defined below. ARPA-E will assume a 50% mass and volume packing fraction for cells in systems for the purposes of this FOA. However, projects where cell and/or system architecture innovations are core to the proposed innovative technology approach may assume other mass and volume packing fractions if they can be well justified. System level metrics may be estimated using reasonable assumptions, which must be clearly stated.

The Primary Technical Requirements and Secondary Technical Targets for this FOA are clearly stated in the two tables below.

PRIMARY TECHNICAL REQUIREMENTS:

Requirement ID Number	Requirement Category	System Value (Units)	Cell Value (Units)
1.1	Specific Energy Density (at C/3 discharge rate)	200 Wh/kg	400 Wh/kg
1.2	Volumetric Energy Density (at C/3 discharge rate)	300 Wh/liter	600 Wh/liter
1.3	System Cost	Realistic potential for < $250 / kWh (System)	

SECONDARY TECHNICAL TARGETS:

Target ID Number	Target Category	Description
2.1	Specific Power Density (80% Depth of Discharge, 30s)	400 W/kg (system), 800 W/kg (cell)
2.2	Volumetric Power Density (80% Depth of Discharge, 30s)	600W/liter (system), 1200 W/liter (cell)
2.3	Cycle Life	1000 cycles at 80% Depth of Discharge (cell/system), with cycle life defined as number of cycles at which a >20% reduction in any energy/power density metric occurs relative their initial values
2.4	Round Trip Efficiency	80% at C/3 charge and discharge
2.5	Temperature Tolerance	-30 to 65C, with <20% relative degradation of energy density, power density, cycle life and round trip efficiency relative to 25C performance
2.6	Self Discharge	<15%/month self discharge (of initial specific energy density or volumetric energy density)
2.7	Safety	Tolerant of abusive charging conditions and physical damage without catastrophic failure
2.8	Calendar Life	10 years

ARPA-E will not consider selecting projects for award that do not clearly demonstrate realistic, well-justified potential to meet or exceed the Primary Technical Requirements stated above by the end of the period of performance. Furthermore, ARPA-E will give particularly strong consideration to projects that can significantly exceed these Primary Technical Requirements.

With regard to Primary Technical Requirement 1.3, the system level cost requirement, ARPA-E understands that not all applicants will have access to sophisticated battery system cost modeling. It is expected that all applicants will make a strong effort to estimate the potential materials and manufacturing costs of the proposed technology to justify how the technology holds promise to approach, meet, or exceed this FOA's $250/kWh system level cost target.

ARPA-E expects that all novel high energy density battery approaches with low cost potential that have strong potential to meet or exceed the Primary Technical Requirements for this FOA will likely have unique technology challenges in meeting one or more of the Secondary Technical Targets for this FOA, and thus ARPA-E will expect that each proposed technology development plan will have strengths and weaknesses as it relates to its ability to meet or exceed one or more of the Secondary Technical Targets. Thus, proposed battery technology research and development plans with end of project performance target shortcomings relative to one or more Secondary Technical Targets will not be precluded from consideration for selection for award. However, it is expected that all proposed battery technology research and development plans will at least approach the stated Secondary Technical Targets by the end of the project period of performance and proposals will be evaluated against the proposed technology research and development plan's ability to do so.

ARPA-E will set aggressive intermediate "go-no go" metrics for each project selected for award under this FOA and will use independent external partners to validate the demonstrated performance of all battery prototype devices/systems developed under this FOA, including standard tests of safety/abuse tolerance and accelerated testing to determine calendar life

B.4.2 Other Technical Requirements

In addition to the Primary Technical Requirements and Secondary Technical Targets detailed above, applicants must address the following key technical requirements.

A. Manufacturability of Proposed Technology at Scale

The applicant must describe the manufacturing approach(es) that will most likely ultimately be used to scale up the proposed battery technology to be prototyped in the proposed research and development project and must discuss the ability of this/these manufacturing approach(es) to scale at sufficiently low cost to address the $250/kWh Primary Technical Requirement. The applicant is also encouraged to describe whether or not the proposed battery technology offers an opportunity for the U.S. to take a leadership role in battery manufacturing and to provide justification.

B. Technical Strength of the Performance Team

The applicant should describe the unique elements/background/skills of the proposed technical team that make the team uniquely suited to successfully execute the proposed battery research and development plan.

B.5. CONCEPT PAPER STRUCTURE

Applicants are required to first submit a Concept Paper describing the essence and novelty of their new technology concept in order to be considered for award under this FOA. The purpose of the Concept Paper phase of this FOA is to allow applicants to communicate their battery technology concept to ARPA-E, with a minimal level of investment in time and resources, and receive feedback on ARPA-E's level of interest in the concept before ARPA-E requests the submission of a more time and resource intensive Full Application.

General Concept Paper requirements can be found in Section IV.B.2 of this FOA. Specific requirements and key elements that each Concept Paper must address are found in this section (Section I.B.5) and in the rest of Section I.B.

As stated in Section IV.B.2, Concept Paper will consist of a body not exceeding five (5) pages in length containing the following sections: 1.) Abstract and 2.) Technical Section. The Concept Paper will also include a one page "Cost Summary" (described in Section IV.B.2) and a one page completed "End of Project Targets" table that should be included in a single Concept Paper file, but will not count toward the five (5) page Concept Paper body limit. The End of Project Targets table will include the end of project target for the scale and form factor of the prototype device deliverable, as well as the end of project targets for all Primary Technical Requirements and Secondary Technical Targets. The "End of Project Targets" template can be found in Appendix 1 in Section X.

TECHNICAL SECTION

Specific issues/questions that should be considered and addressed in the Technical Section include the following:

- Identification of whether the applicant is applying for an award under the "Proof of Concept Seedling" category or the "Advanced Device Prototyping" category.
- A detailed description of the novel technology approach to be developed in the proposed project, including a description of its basic operating principles of how the proposed approach is unique and innovative.
- A description of the current state-of-the-art in the proposed technology area, including key shortcomings/limitations/challenges, and how the proposed project will seek to significantly improve upon the current state-of-the-art performance and overcome current key shortcomings/limitations.
- The applicant should provide a brief paragraph addressing the following issues for each of the Primary Technical Requirements (1.1-1.3) and Secondary Technical Targets (2.1-2.8)
  - What is the current state-of-the-art performance level for the proposed technology area for the specified requirement/target?
  - What level of performance will the project proposed here target for the specified requirement/target? What are the specific technical issues that have limited performance of this technology to date for the specified requirement or target?
  - How does the project proposed here address these specific technical issues to provide enhanced performance relative to the specified requirement or target? The applicant should provide technical justification for why this proposed target can credibly be met.
  - What are the key technical risks/issues associated with the technology development plan related to the specified requirement or target?
- A brief description of the manufacturing approach by which the proposed battery technology would most likely be scaled and the scalability/cost issues related to this approach.
- A brief description of how the project, if successful, would impact U.S. leadership in battery technology development and manufacturing.
- A brief description of the project team and why they are uniquely suited to successfully execute the proposed battery research and development plan.
- A brief description of the impact ARPA-E funding of the proposed project would have relative to other previous or existing funding sources the project team has secured.

B.6. CONCEPT PAPER EVALUATION CRITERIA

General Concept Paper Evaluation Criteria are found in Section V.A. of this FOA. More specific Concept Paper Evaluation Criteria are described in this section.

Concept Papers will be evaluated against the following evaluation criteria in decreasing order of importance:

- To what degree does the Concept Paper present a battery technology development plan that demonstrates credible and well-justified technical potential to meet or exceed each of the Primary Technical Requirements of this FOA. Technology approaches will be evaluated in a quantitative fashion, with technology approaches rated according to the degree to which they fall short of, meet, or exceed each quantitative Primary Technical Requirement.

- To what degree does the Concept Paper present a battery technology development plan that demonstrates credible and well-justified technical potential to meet or exceed each of the Secondary Technical Targets of this FOA. Technology approaches will be evaluated in a quantitative fashion, with technology approaches rated according to the degree to which they fall short of, meet, or exceed each quantitative Secondary Technical Target.
- To what degree does the Concept Paper present a unique and innovative technical approach to significantly improve battery performance over the current state-of-the-art
- To what degree does the Concept Paper present a clearly demonstrated understanding of the current state-of-the-art and technical limitations of the current state-of-the-art in the relevant technology area.
- To what degree does the battery technology proposed in the Concept Paper hold potential to enable U.S. manufacturing leadership in EV battery systems.
- To what degree does the proposed technical team have the skills and knowledge to successfully execute the project plan
- To what degree will ARPA-E funding have a leveraged impact on the development of the proposed technology relative to other funding sources for the project team.