U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002972
on
Rethinking Energy Storage Technologies for Planes, Trains & Ships
"Battery 1K"

Summary:

The purpose of this RFI is to solicit input for a potential future ARPA-E program focused on energy storage technologies that can deliver a specific energy equivalent to, or exceeding, 1000 watt-hours per kilogram (Wh/kg). Of particular interest are technologies that are not extensions of current mainstream electrochemical device thinking or short-term technology road maps. The goal is to gauge the potential to realize exceptionally high-energy storage solutions that would be capable of catalyzing broad electrification of the aviation, railroad, and maritime transport sectors. ARPA-E is seeking information at this time regarding transformative and implementable technologies that could accelerate electrification of transport including the following industries:

(a) ***Aviation:*** "Battery 1K" can enable regional flight on aircraft transporting up to 100 people.
(b) ***Railways:*** "Battery 1K" can enable cross-country travel in the United States (U.S.) with fewer stops while also reducing the amount of infrastructure needed for charging/refueling.
(c) ***Maritime:*** This is a diverse category but higher energy density options will open up additional electrification possibilities.
(d) ***Trucks:*** Strategies and plans to electrify this sector are in place however, "Battery 1K" would enable longer range and higher freight loads.

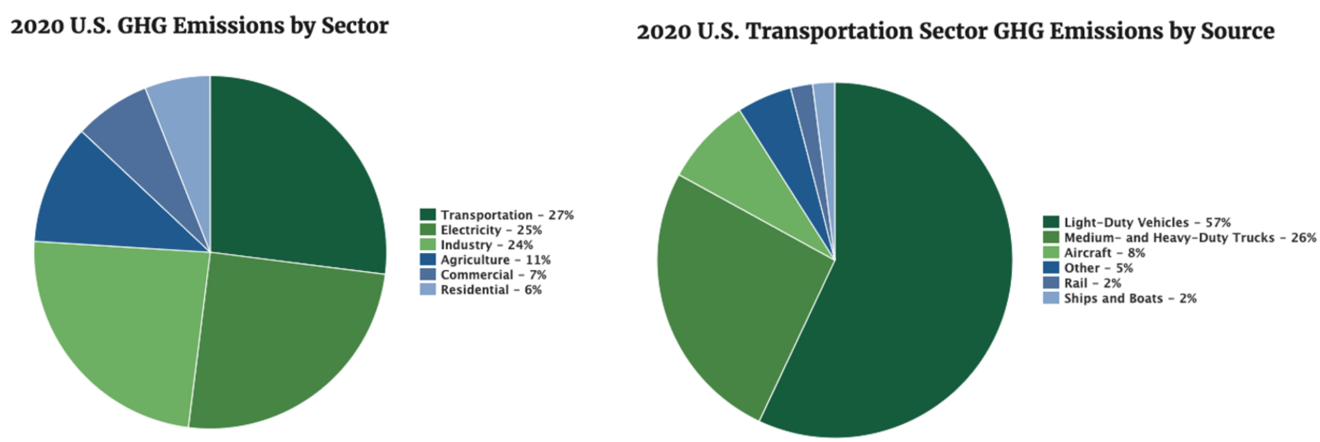
Upon consideration of metrics discussed in the RFI, the traditional energy storage device "playbook" must be cast aside. An overwhelming majority of batteries "live" in boxes, are "plugged-in" to charge, and in the case of personal passenger electric vehicles (EVs) are used only 5% of the time. For the remaining 95%, EVs are typically parked with a battery that is either idle or charging slowly. In sharp contrast, for the transportation sectors of interest to this RFI, the energy storage device may be required to (1) operate continuously over extended periods of time, (2) refuel/recharge/reset rapidly, and (3) achieve exceptional longevity. It is also worth noting that constraints on volumetric energy density are reasonably anticipated to be dependent on the specific application, although perhaps less important than gravimetric energy density in the case of aviation, for example. Certainly, an energy storage technology that can deliver ≥ 1000 Wh/kg and ≥ 2000 Watt-hours per liter (Wh/L) would represent a >3x improvement relative to today's state-of-the-art (SoA) lithium-ion battery (LiB) solutions, and which may be necessary for electrifying the sectors of interest identified in this RFI. As the constraints of classical energy storage thinking are reconsidered, operating temperature, fuels versus oxidizers and the physical boundaries of the energy storage system are all up for grabs. Think less "out of the box" and more that there is no box.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Need – Reduced Greenhouse Gas Emmissions, Increased Power/Energy:

In the U.S., transportation contributes 27% of the greenhouse gas (GHG) emissions[1] and the focus of many organizations to electrify this sector, including the Department of Energy (DOE). , is indeed an appropriate application of attention, effort, and investment. Light duty vehicles, i.e., passenger vehicles and small commercial vehicles, account for 57% of transportation GHG emissions and battery options have justifiably emerged as the most appropriate solution. The energy density of existing battery technologies is considered sufficient while the priority areas for improvement include safety, cost, lifetime, and charge time, along with supply chain sustainability. The majority of the remaining 43% of transportation GHG emissions is attributed to long distance trucking, aviation, maritime, and railroads. The contributions of individual transportation categories to GHG emissions according to the EPA are shown in Figure 1.

Figure 1: GHG emissions (U.S., 2020) by sector (*left*) and transportation sector by source (*right*).



History and Background:

With respect to electrification of passenger vehicles, energy density has historically been the dominant attribute with both gravimetric (Wh/kg) and volumetric (Wh/L) energy density important to varying degrees. Early battery powered cars featured low energy density chemistries such as lead acid or nickel metal hydride[2], although with the advent of commercial LIBs in 1991, new options have emerged. Lithium Ion Battery (LIB) cells with energy densities of 100 Wh/kg and 250 Wh/L were the obvious choice for laptop computers and other consumer devices where volume and weight are the most critical factors. Improvements to energy density, and most importantly cost[3], enabled LiBs to be adopted for electrified passenger vehicles.

Typical SoA LiB cell attributes today include:

- 285 Wh/kg;
- 650 Wh/L;
- 1000 cycles to 80% initial capacity;

[1] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
[2] "The Long Hard Road", Chapter 6, Charles J. Murray, Purdue University Press, 2022, ISBN 978-1-61249-762-4
[3]Bloomber NEF, 3/5/19, https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

- 30-minute charge to 80% of full capacity;
- $120/kWh

Origins of and Perspectives on 1000 Wh/kg Energy Storage:

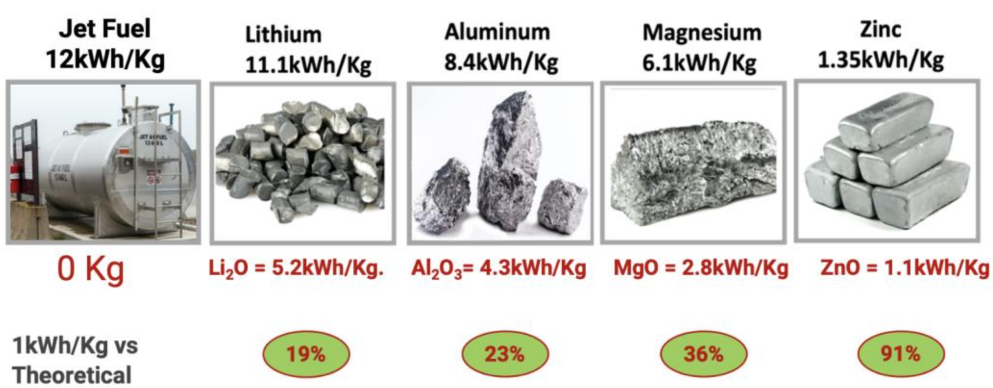
At the ARPA-E Energy Innovation Summit that was held on May 23-25, 2022, the following question was posed during the "Fast Pitch: Transportation Systems" Session: *"What if 1000 Wh/kg could be achieved?"*[4]

The non-fossil fuel based 1000 Wh/kg energy density target that was highlighted at the Summit, and that is the focus of this RFI, is significant since it:

i) Appears to offer the potential for fossil fuel-free operation for regional flight and cross-country railways.
ii) Represents a 3-4x increase in energy density compared to today's SoA LiB, which is 3x higher in value than the first commercial LiBs introduced in 1991.
iii) Demands a transformational technology that cannot be achieved *via* incremental advancements or improvements to existing LiB chemistries.

Anodes in batteries can be considered as fuels in that upon releasing energy, they are oxidized and donate electrons. Following "donation", they can be regenerated either by electrical (i.e., charging) or mechanical (i.e., replacing, recycling or swapping out the "spent" oxidized anode material) methods. As indicated in Figure 2, the energy potential of metals as "fuels" may provide an intriguing proposition.

Figure 2: Theoretical energy densities of metals as fuels presented together with their corresponding oxides. *Note: sodium, calcium and potassium may also have merit.*



Note: Further details can be found in the recording of the ARPA-E Summit. https://www.youtube.com/watch?v=lZ6iQHolab0
Values in red represent the energy density based on the oxidized form that would be retained on board the vehicle. Jet Fuel = 0 because it is is expelled by the jet engine during combustion;1kWh/Kg vs theoretical is 1/metal oxide weight expressed as a percentage (%).

Trade-offs and the Development Journey:

Global energy consumption is expected to increase by 50% between now and 2050[5]; at the same time, there exist strong aspirations to achieve net zero or even negative regarding GHG emissions. One thing

[4] https://arpa-e.energy.gov/sites/default/files/5-Fast_Pitch_Final_CHEESEMAN.pdf
[5] https://www.eia.gov/outlooks/ieo/

is certain – a multitude of technologies and strategies will be required to achieve these ambitious climate goals.

Historically, energy storage devices have taken an extended period to develop and commercialize. Although the fundamental underlying mechanisms for lithium-ion were discovered in the 1970s and a cathode to enable those primary processes was identified in 1980, the first sale of LIBs did not occur until 11 years later (1991)[6] Further, it has taken an additional 20 years for LiBs to achieve the energy and cost needed to position the technology as the leading option for EVs. Assuming an energy storage solution that can deliver 1000 Wh/kg is possible, then the reality is that development needs to be initiated soon if it is to have a chance of realizing a meaningful impact towards the 2050 net zero climate goal. Further, federal, state, and private sector focus, effort and investment must be a priority if the U.S. is to assume a global technology leadership role in the future.

EVs introduced in the early 2000s delivered energy and power, yet other attributes received lower priority. As battery technologies progress into the 2020s, factors such as lifetime, cold temperature performance and charge time are receiving increasing attention. The electrification journey for aviation, railroads and maritime transport is expected to have similar phases, with performance sufficient for early demonstration and design work that will be less demanding relative to the more challenging-to-attain attributes ultimately required for successful, profitable, and mature commercialization.

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES:

ARPA-E is not accepting applications for financial assistance or financial incentives under this RFI. Responses to this RFI will not be viewed as any commitment by the respondent to develop or pursue the project or ideas discussed. ARPA-E may decide at a later date to issue a FOA based on consideration of the input received from this RFI. No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on Wednesday, March 8, 2023.** Emails should conform to the following guidelines:

- Please insert "Response to RFI DE-FOA-0002972" in the subject line of your email, and include your name, title, organization, type of organization (e.g., university, non-governmental organization, small business, large business, federally funded research, and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.

[6] "The Long Hard Road", Chapter 5, Charles J. Murray, Purdue University Press, 2022, ISBN 978-1-61249-762-4

- Responses to this RFI are limited to no more than 5 pages in length (12-point font size
- Optionally, responders are welcome to discuss available results and/or data to reinforce the perspectives provided.
- Please indicate the RFI questions (1, 2, 3, etc.) being addressed whenever possible.

Questions:

ARPA-E is interested in surveying stakeholders interested in electrification of transportation as outlined above. Additional guidance for developing responses is provided in this section. Please provide responses and information about any of the following. ARPA-E does not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the group and question number in your response. Citations are encouraged as appropriate.

The objective of this RFI is to motivate responses to the primary question of whether there exist enough transformational concepts to potentially justify a new program that focuses on a 1000 Wh/kg target. When developing responses to this RFI, factors such as cost, supply chain, manufacturability and/or compatibility with existing operations should be viewed as being of lower importance. Although health, safety and environmental considerations are not a primary focus at this stage, solutions that are inherently unsafe, have an unfriendly environmental footprint and/or adverse toxicity profile, may realistically be limited in potential.

Responses to this RFI should consist of a four-page document that identifies, and describes in comprehensive technical detail, energy storage concepts and solutions that may be capable of achieving the 1000 Wh/kg target. In addition to developing responses to the questions below, please attempt to provide values for as many of the key energy storage parameters as possible in Table 1 and include in the response. *Note:* It is <u>not</u> a requirement to provide answers to all questions in the response. To be determined (TBD) is an acceptable entry in Table 1 at this stage, especially if confidence in the accuracy of values is low.

Table 1: Energy storage parameters of interest to this RFI.

Key parameter	As modeled	As experimentally demonstrated	As projected (commercialized)
Onboard gravimetric energy density (kWh/Kg)			
Onboard volumetric energy density (kWh/L)			
Refuel, recharge, reactivation time			
Power capability (kW/kg)			
Life expectation (years and cycles)			
Temperature operating range (^oC)			
Other (See RFI questions 1-20)			

Note: Please add notes if the numbers inserted in Table 1 are application-specific.

RFI Questions:

1. Provide a brief description of the technology(ies) capable of achieving the 1000 Wh/kg energy density target – combinations of text, figures, and/or illustrations are permissible. Please include all elements of the energy storage device and the mechanism for recharge/refuel.
2. What is the basis for the energy density values that may have been provided in Table 1? Do they consider only actives? Cells? Modules, stacks, packs? Do they include balance of plant? Thermal components, heaters, BMS, pumps, pipes, valves and everything else net to the application, etc?
3. Are there particular executions of this technology where gravimetric energy density can be maximized versus other metrics?
4. How do you envision the energy storage system/key components will be recharged, refueled, reactivated, re-smelted, recycled, swapped out, etc. between application uses?
5. What type of packaging, thermal management and electronic management would said technology require?
6. Beyond Q5, are there any additional hardware requirements, balance of plant, and/or special equipment required within the application of use?
7. What hardware requirements, balance of plant, and/or special equipment do you envisage might be required outside of the application that would be needed *between* uses (e.g., chargers, hoists, materials handling, materials processing, recharger, storage vessel(s), etc.)?
8. Are you aware of the scale at which this technology may have been previously demonstrated, including size, energy, and power?
9. How would you best describe the current development stage of this technology? Conceptual? Research stage? Applied research, development, and engineering stage? Pilot line? Early commercialization stage? Other? Please consider your response within the context of roadmaps (For example, Gen 1, Gen 2, and Gen 3 may be at different stages).
10. What applications might this technology be best suited for?
11. What applications would this technology probably not be appropriate for?
12. How would you describe the prior art relating to this technology?
13. Would this technology require additional heating or cooling to work effectively?
14. Would this technology need to be maintained at specific conditions (temperature, for example) during or between uses?
15. What Wh round trip efficiency might be expected for this technology when implemented in its most likely application?
16. Do you have any perspectives on commercialized cost on an energy basis (e.g., $/kWh)? As you are able please comment on the relative capital costs (CAPEX) and operational costs (OPEX) that will be involved.
17. Is there any information available to substantiate potential safety, toxicity, or environmental impact of this technology?
18. Do you have any information on the carbon footprint relating to the production of this energy storage system? Please ensure that you consider the factors in your answers to 4, 5, 6, and 7.
19. How would you describe the manufacturability of this technology?
20. Is there anything else you would like to share about this technology?