US Department of Energy
Advanced Research Projects Agency-Energy

Request for Information (RFI)
DE-FOA-0002468
on
Stationary Hydrogen Storage Technology Development

Abstract

The purpose of this RFI is solely to solicit input for ARPA-E's consideration and to inform the possible initiation of an R&D program on stationary hydrogen storage technologies. In particular, ARPA-E is interested in information regarding safe, low-cost, flexible scale from large to small, transportable, and widely deployable hydrogen storage technology for ultralong-duration seasonal energy storage. The hydrogen storage systems of interest are turn-key systems ready to be integrated with hydrogen fuel cell power generation, hydrogen capable CHP, microgrid, and other distributed power generation systems. The goal is to develop technologies and validate their reliability under variable conditions, manufacturability, and favorable economics at scale.

The growth of renewable energy is gaining momentum. Power generation from solar panels, wind turbines, and other renewable sources in the first five months of 2020 reached 25% in the US. However, the continued growth and deep penetration of renewable energy to greater than 50% require long-duration energy storage on a massive scale. While battery technologies can meet applications requiring hours of energy storage, and novel technologies such as those being developed in the ARPA-E DAYS program can satisfy applications requiring a day or more of storage, a need remains for energy storage technologies can dispatch over weeks or even months. Current technologies for long-duration energy storage, such as pumped hydro, are usually geographic location limited and require ultra-large-scale infrastructure investment and long-term commitments.

One of the options for large scale renewable electricity storage is to produce hydrogen using the surplus renewable electricity that would otherwise be curtailed or when electricity is available at low cost. Hydrogen, however, must be stored before it can be converted back to electricity or used for other purposes. Methods for hydrogen storage have their own challenges, from geographic location requirements to capital costs to conversion efficiency. If low-cost hydrogen storage can be achieved, however, it can contribute to enabling a deeply decarbonized power grid.

The Advanced Research Projects Agency-Energy (ARPA-E) of the US Department of Energy seeks information that could inform ARPA-E's potential research and development (R&D) funding for safe, low-cost, flexible scale, transportable, and widely deployable hydrogen storage technologies for ultralong-duration, especially seasonal, energy storage. The hydrogen storage systems of particular interest should be turn-key systems ready to be integrated with hydrogen fuel cell power generation, hydrogen capable CHP, microgrid, and other distributed power generation systems.

Background, Scope, and Objectives

Seasonal Energy Storage

In the last decade, renewable energy, especially the power generation from solar panels and wind turbines, has doubled. Total electricity generation from renewable sources in the first five months of 2020 reached 25% in the US. Solar and wind account for the majority of the growth. Solar and wind now represent the cheapest available sources of electricity in several regions. However, the continued growth and deep penetration of renewable energy face challenges due in part to the variability of renewable sources. The renewable sources vary depending on the hours of the day and month or season of the year. The variations cause difficulties in the deployment and management of power generation assets, curtailment of power productions, and grid stability management. In order to address the variability and maintain the stability of power supply to end-users, energy storage systems must be built into the power production and supply system.

Energy storage systems can be categorized based on the duration of storage, as shown in figure 1[1]. As a result of the advancement of electric battery technologies in the recent decade, batteries are currently the most cost-effective method for energy storage for up to 10 hours. Advanced technologies are being developed to extend the storage duration up to days (100 hours)[2]. For energy storage beyond a week or seasonal energy storage, there are few options. Current technologies for long-duration energy storage, such as pumped hydro, are usually geographically location limited and requires massive scale infrastructure commitment and investment. The cost of large scale siting limited long-duration storage of electricity depends not only on the cost of storage itself but also the need for the construction of the infrastructure and the cost of transmission/transport from where it is stored to where it is needed.

It is noted that seasonal energy storage has always been needed and has been done for decades. Seasonal energy storage has mostly been done by the storage of fossil energies, especially natural gas. It is estimated that 4000 billion cubic feet of natural gas, approximately 15% of total annual energy consumption in the US, is stored to meet the heating demand spike in winter.

[1] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/52794883
[2] https://arpa-e.energy.gov/technologies/programs/days

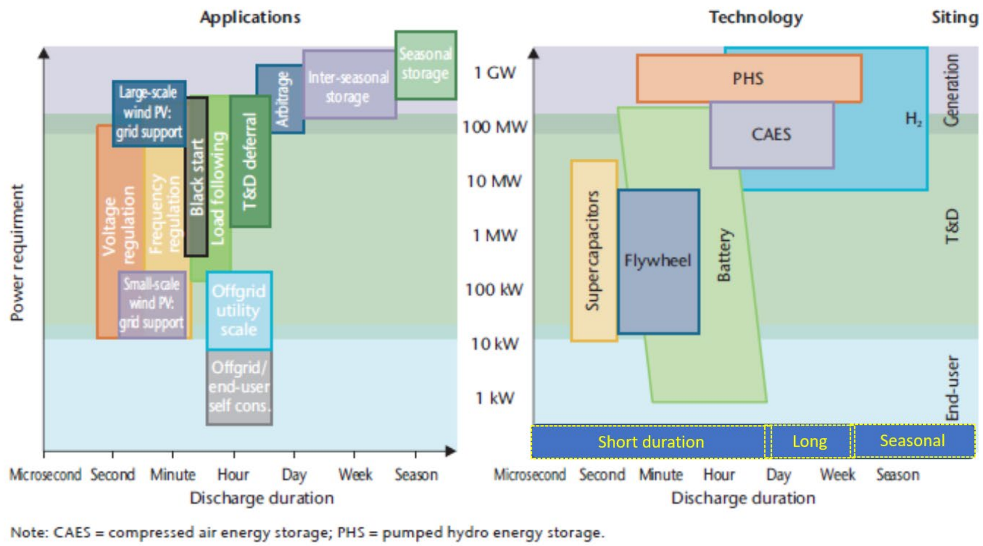


Figure 1. Energy storage technologies, their applications and durations.

One of the emerging options for large scale renewable electricity storage is to produce hydrogen using the surplus renewable electricity that would otherwise be curtailed to split water electrolytically. The hydrogen can be stored and converted back to electricity when it is needed. Figure 2 schematically illustrates this approach. This approach makes electricity one hundred percent clean.

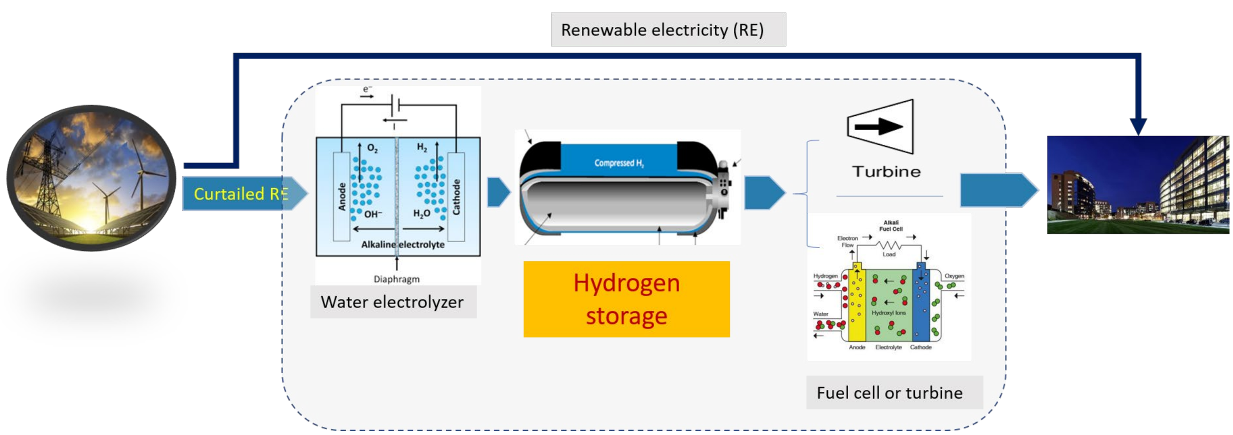


Figure 2. Schematic illustration of the long-duration seasonal energy storage system consisting of a water electrolyzer for producing hydrogen, hydrogen storage tank, and the conversion of hydrogen back to electricity.

However, the challenge is the roundtrip efficiency from electricity to hydrogen and to electricity is low compared to the storage based on the electric battery. Li-ion batteries are most effective for short duration storage; the energy storage via hydrogen aims to resolve the challenges for seasonal storage. Seasonal energy storage based on hydrogen is a more cost-effective option than pumped-hydro storage based on a recent modeling study published by NREL[3]. Hydrogen storage with just one week's duration could become cost-effective by achieving capital costs for the power equipment below $1,507 per kW, and capital costs for underground hydrogen storage below $1.80 per kWh. The results of the model were based on the assumption that hydrogen storage is accomplished by using salt caverns on a large scale.

Hydrogen Storage

Owing to the boundless potential of hydrogen for a carbon-neutral or carbon zero future green hydrogen technologies are gaining momentum rapidly around the world. In the United States, the H2@Scale initiative and the recently published Hydrogen Program Plan[4] by the US Department of Energy (USDOE) underscores both the importance and urgency for the development of hydrogen technologies to achieve both national and global goals to address the threat of climate change.

Hydrogen is a central pillar of the energy transformation required to limit global warming to two degrees Celsius. The world will need to make dramatic changes year after year and decrease energy-related CO_2 emissions by 60% until 2050 to achieve the two-degree scenario[5]. Achieving the hydrogen vision would create significant benefits for the energy system, the environment, and businesses around the world. It would avoid 6 Gt of CO_2 emissions, create a $2.5 trillion market for hydrogen and fuel cell equipment, and provide sustainable employment for more than 30 million people[5]. Hydrogen technologies encompass a suite of technology areas and challenges that must be met before hydrogen can play a significant role in reaching the climate goals. These technology areas and challenges include the production of green hydrogen, storage and delivery of hydrogen, and the widespread adoption of hydrogen in power production, transportation, and manufacturing industries. Among them, hydrogen storage is an essential and indispensable link that plays a critical role across all areas of hydrogen technologies' successes or failures.

Hydrogen can be stored in a number of different ways, as listed below.

- In gaseous form
    - Salt caverns
    - Rock caverns
    - Depleted oil and gas wells
    - High-pressure tanks
- In liquid form
    - Liquid hydrogen
    - Ammonia
    - Liquid organic hydrogen carrier

[3] Omar J. Guerra et al. 'The value of seasonal energy storage technologies for the integration of wind and solar power, Energy & Environmental Science, Issue 7 2020

[4] https://www.nrel.gov/docs/fy21osti/77610.pdf

[5] https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf

- In solid form
    - Metal hydrides
    - Adsorbents

These storage methods can also be classified into two categories: on-board mobile storage and stationary storage. The on-board hydrogen storage for fuel cell vehicles has been the focus of the hydrogen storage R&D for the most recent 20 years and as far back as in the 1970s. For on-board applications, the hydrogen storage system must meet a stringent set of properties, including both gravimetric and volumetric energy densities, operating temperature, hydrogen release and refueling kinetics, and safety concerns. The current state-of-the-art hydrogen storage technology for fuel cell vehicles is the high-pressure tank storage at 700 bar hydrogen pressure. The safety concerns and the less than desired energy density of high-pressure tanks have dictated the high cost of these technologies.

As the name suggests, stationary hydrogen storage is stationary and is needed wherever hydrogen is produced and wherever hydrogen is used. It is a critical and ever-present part of the hydrogen supply chain. Currently, stationary hydrogen storage is mostly done by using high-pressure tanks with pressures ranging from 350 to 700 bar in most applications, while in some cases in salt caverns for large scale storage where salt caverns are available. Hydrogen can also be stored in liquid media, e.g., liquid hydrogen, liquid ammonia, or liquid organic hydrogen carriers.

Among these technologies, storing hydrogen in salt caverns is the lowest-cost approach for large scale storage. However, salt cavern storage is limited by geography and geology. It requires infrastructure such as pipelines to deliver hydrogen from where it is produced to where it is needed. The storage in high-pressure tanks is the most convenient and versatile approach that is used today. However, high-pressure tank storage has significant inherent safety risks, which results in high capital costs. Liquid forms of storage methods usually have higher energy density than the gaseous storage methods and are the best for transportation and delivery of hydrogen in the absence of pipelines. The challenge is the roundtrip efficiency; conversion to the liquid and back into hydrogen results in around 45% loss in energy[6].

Hydrogen can also be stored in solid forms such as in metal hydrides or solid absorbent. Compared to other methods, such as high-pressure tanks, in particular, storing hydrogen in metal hydrides has the advantages of being safer because it usually does not require high pressure and more compact because it can have 3-4 times higher volumetric hydrogen capacity than high-pressure tanks. However, although the research on solid material-based hydrogen storage is a high visibility research area for on-board hydrogen storage applications, there are few reports on the potential application of solid material-based storage method for stationary hydrogen storage

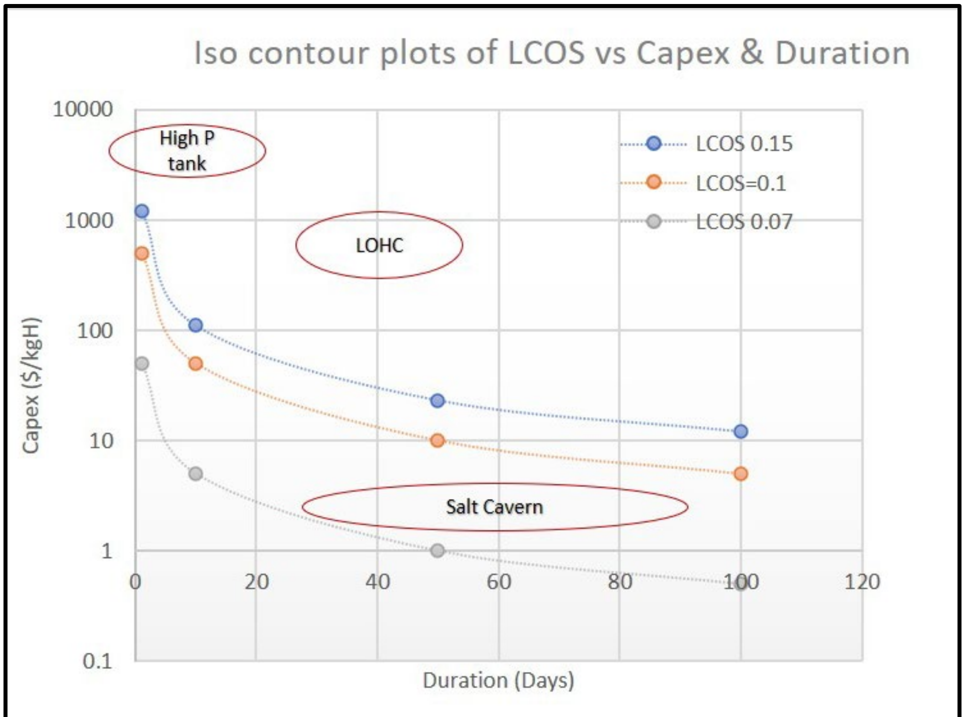
[6] Transportation and storage costs calculated using data from: Curley, M., Pipeline and Gas Journal (2008) 235, 34; Ramsden, T., et al., "Hydrogen Pathways", NREL report TP-6A10-60528; Bartels, J. R. and Pate, M. B., "A feasibility study of implementing an Ammonia Economy", Iowa State University, 2008; Schoenung, S., "Economic Analysis of Large-Scale Hydrogen Storage for Renewable Utility Applications", Sandia report SAND2011-4845 (2011);

A key difference between the on-board hydrogen storage and stationary hydrogen storage is that the gravimetric hydrogen density requirement is significantly relaxed for stationary storage. This opens the field with many candidate materials that could enable the successful development of hydrogen storage systems. However, a successful hydrogen storage system for long-duration seasonal energy storage still have to meet a host of stringent requirements, including the safety requirements, hydrogen release and refueling kinetics, operational temperature, maximization of volumetric and gravimetric hydrogen density, heat management during charging and recharging, energy loss minimization, and perhaps most importantly, the need to be cost-competitive.

Hydrogen has to compete with other technologies to offer economically viable energy storage. The cost of green hydrogen produced from water electrolyzers, the efficiency of the conversion from hydrogen back to electricity, and the cost of hydrogen storage all play significant roles in determining the final cost of electricity delivered. The cost impact of storage depends not only on the capital cost but also on its duty cycle, which is closely related to the duration of storage. Long duration storage would mean less frequent hydrogen cycling, which contributes to driving up the cost on a unit energy basis.

Figure 3 shows the Levelized cost of storage (LCOS) expressed as the cost of electricity delivered after the entire process from power-hydrogen-power. It shows that among various technologies for hydrogen storage, the salt cavern is currently the least-cost option. However, there are multiple options that do not require large scale infrastructure investment and of which the cost could be reduced to become competitive with salt caverns. Salt cavern and high-pressure tank storages are mature technologies, while the other options are, for the most part, at lab scale.

There are great motivations and high impact opportunities to develop alternative hydrogen storage technologies. ARPA-E seeks to develop step-change stationary hydrogen storage technologies that can deliver electricity at the cost equivalent to that of salt caverns without the siting limitations. The new technologies must be safe, low-cost, scalable from small to large, compact, transportable, and deployable anywhere. ARPA-E envisions that technologies developed in this program will become a ubiquitous hydrogen storage method that enables long-duration seasonal energy storage at all scales: large, medium, and small.



LCOS-levelized cost of storage ($/kWh), LOHC-liquid organic hydrogen carrier.

Figure 3. Contour plots of the levelized cost of storage expressed as the cost of the electricity delivered as a function of capex and duration of storage.

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E's consideration and to inform the possible initiation of an R&D program on stationary hydrogen storage technologies. In particular, ARPA-E is interested in information regarding safe, low-cost, flexible scale from large to small, transportable, and widely deployable hydrogen storage technology for ultralong-duration seasonal energy storage. The hydrogen storage systems of interest are turn-key systems ready to be integrated with hydrogen fuel cell power generation, hydrogen capable CHP, microgrid, and other distributed power generation systems. The hydrogen storage technology developed will also have enabling effects for hydrogen in a broad range of other industries where hydrogen will be stored and used, including hydrogen distribution centers, chemical plants, industrial heating, and hydrogen fueling stations.

The goal is to develop technologies and validate their reliability under variable conditions, manufacturability, and favorable economics at scale. Successful stationary hydrogen storage technologies would establish a path forward to continued private sector development, scaling, and deployment of these technologies. Ideally, the designed and constructed hydrogen storage units would serve as a test site for future scale-up benchmarking.

This research effort, if successful, would catalyze the widespread adoption of hydrogen for long-duration and seasonal renewable energy storage, enable deeper penetration of renewable electricity, reduce the carbon emissions of the power generation sector, and establish a new manufacturing base for energy technology in the US.

Responders should provide the following information, though a response to each item on the list is not required. The questions are grouped into different categories.

Long-duration energy storage

1. Describe the current commercially available technologies for seasonal energy storage, including scale (total energy) and the number of deployments. What are the technology gaps and pain points of current technologies for long-duration and seasonal energy storage?
2. What are emerging/pre-commercial technologies for long-duration and seasonal energy storage, and at what scale have they been demonstrated?
3. What are the economics of seasonal energy storage, and what are the appropriate metrics for seasonal energy storage?
4. What are the outlooks for centralized versus distributed renewable power generation and how that may impact long-duration and seasonal energy storage?
5. How do capacity factor variations impact the selection and deployment of long-duration storage technologies?
6. At what duration can an energy storage system replace existing or planned assets used for system capacity and reliability?

Stationary hydrogen storage, scale, metrics

7. What are the outlooks for the role of hydrogen in long-duration and seasonal energy storage?
8. Describe the current commercially available technologies for stationary hydrogen storage, including scale and the number of deployments. What are the technology gap and pain points of existing technologies for stationary hydrogen storage?
9. Describe pre-commercial options for stationary hydrogen storage?
10. What should be the metrics for stationary hydrogen storage?
11. What is the scale or range of scales of individual hydrogen storage technologies that would be optimal for demonstrating scalability?

Stakeholders and markets

12. Describe what you view as the major technical and market risks associated with developing stationary hydrogen storage technologies?

13. What are the major challenges in using hydrogen storage systems to store intermittent power, and how can they be overcome?
14. Describe the key stakeholders that would enable the development and deployment of stationary hydrogen storage technologies. Please identify if you are a stakeholder

Organizational capabilities

15. Capabilities and needs of organizations to provide or evaluate such ARPA-E funded technologies
16. Capabilities and needs of organizations to develop, integrate, build, and test a stationary hydrogen storage system
17. Describe a typical project timeline including key milestones, approximate budget, and expected deliverables for stationary hydrogen storage technologies
18. Describe the need for partnering, and typical team compositions, to advance hydrogen storage and related technologies to market.

In addition, ARPA-E seeks information that also addresses:

- Forming teams with more diversified professional engineering and management capabilities needed for large R&D projects.
- Encouraging engagement with industry stakeholders providing in-kind support to the system integration effort. These stakeholders could be state development agencies, potential customers, investment diligence organizations, project financiers, or others with the ability and interest to facilitate the eventual translation of technology from the bench to commercial scale.

Request for Information Guidelines

Carefully review the REQUEST FOR INFORMATION GUIDELINES below. In particular, 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.**

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 broader research community with an opportunity to contribute views and opinions regarding the current state of the art of ammonia synthesis research and development.

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 a compendium of responses publicly. **Respondents shall not include any information in response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to ARPA-E-RFI@hq.doe.gov by **5:00 PM Eastern Time on March 15, 2021**. Emails should conform to the following guidelines:

- Insert "Response to RFI on Stationary Hydrogen Storage Technology Development - <your organization name>" in the subject line of your email.
- In the body of your email, 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.
- Responses to this RFI are limited to no more than ten pages in length (12-point font size).