A Review of Emerging Energy Storage Technologies

Recommendations for the U.S. Department of Energy

June 25, 2018

ELECTRICITY ADVISORY COMMITTEE

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1 Introduction

Previous work products from the Electricity Advisory Committee (EAC) covering energy storage have focused almost exclusively on *electricity-in/electricity-out* storage (e.g., batteries, compressed-air energy storage, flywheels, supercapacitors, and pumped hydroelectric storage) technologies.[1] Most of these technologies convert electrical energy into another form of energy for the purpose of storage. This energy is then reconverted into electrical energy for delivery to the power system when it is needed.

The purpose of this white paper is to examine other emerging energy-storage technologies that are attracting renewed interest and attention. In many cases, these are technologies that use *electricity-in but not necessarily electricity-out*. These forms of energy storage can perform many functions that are similar to *electricity-in/electricity-out* storage by meeting end-use electricity demands with energy services that can be derived from electricity as an input. Given this technical characteristic, these technologies may be considered as being more akin to demand response than energy storage.

The goal of this survey is to bring these technologies to the attention of the Department of Energy (DOE). It provides recommendations to update pertinent guidance documents and ensure that these technologies are adequately reflected in the DOE's activities. This white paper may also serve as a foundation for further recommendations to the DOE in the future on specific issues related to these emerging energy-storage technologies that may warrant action by the DOE.

2 Approach

The Energy Storage Subcommittee (ESS) of the EAC formed a working group to develop this paper. Research was informed primarily by discussions conducted among working group and ESS members. Once a mature draft was available, further input was provided by experts within the DOE's Office of Electricity and Office of Energy Efficiency and Renewable Energy. The initial focus on surveying and describing emerging energy-storage technologies was broadened to identify definitional issues that are raised by some emerging energy-storage technologies.

3 Key Findings

A number of these emerging energy-storage technologies are conducive to being used at the customer level. They represent significant opportunities for grid optimization, such as load leveling, peak shaving, and voltage control to increase reliability and resilience. The economic viability and attractiveness of these technologies for large-scale adoption, particularly at the customer level, would be significantly affected by the availability of time-varying retail electricity pricing or other mechanisms to incentivize their adoption and use. Another issue that some of these technologies face is that embedding energy-storage capabilities within electrical devices can reduce the energy efficiency of the device. This is due to the energy losses inherent in storing energy. Nevertheless, the added flexibility and ability to manage energy-demand and energy-production patterns afforded by the energy-storage capability may be a "net benefit" despite the lower device efficiency. Many of these technologies are mature and commercially available, while others need further development.

3.1 Thermal Storage

Thermal storage uses electricity as an input to either cool or heat water or another storage medium where the energy is stored to serve subsequent cooling or heating needs. For instance, the thermal energy that is stored in ice or chilled water can be used for cooling (e.g., air conditioning), while energy that is stored in hot water may be used for delivering hot water or other heating purposes when needed. This functionality can be used to flatten load curves.

Many electric co-operatives have a long history of controlling electric water heaters to manage power flows on rural transmission and distribution systems, utilizing baseload generation capacity overnight instead of during daytime peak hours. Similarly, France has deployed electric-water-heater controls as a strategy to manage electric loads with a relatively inflexible nuclear-dominated power supply. Ice and chilled-water storage systems have been used by large customers to flatten their load profiles and reduce demand charges. All of these use cases are adaptable to a changed system design and market environment in which variable renewables are becoming significant sources of energy supply and may be used as the sources for the charging energy.

We observe 10 primary options for thermal energy storage available for deployment today (see Appendix A for their descriptions).

1. Direct load control of resistive electric water heaters
2. Direct load control of electric heat pump water heaters
3. Chilled-water storage
4. Ice storage
5. Chilled energy storage for inlet air cooling
6. Heat pump/borehole
7. Ceramic bricks
8. Molten salt
9. High-temperature phase-change materials
10. Space heating

3.2 Chemical Storage

Chemical storage uses electricity to produce a chemical, which later can be used as a fuel to serve a thermal load or for electricity generation. We see two attractive alternatives for chemical energy storage (see Appendix B for their descriptions).

1. Hydrogen (H_2)
2. Ammonia (NH_3)

3.3 Definitional Issues

A challenge in identifying emerging energy-storage technologies is that there sometimes is not a clear delineation between energy storage and other technologies that may be defined as demand response.

For example, controlled water pumping may be viewed as a demand-response service, insomuch as demand for electricity to operate water pumps is shifted in time; however, this shifting of electricity demand is functionally equivalent, in many respects, to the use of a battery (or any other energy-storage technology) for load-leveling or peak-shaving purposes. The example of a fuel cell-based hydrogen storage system that is co-located with a generator (see Appendix B) has many operating capabilities and characteristics that are akin to a highly flexible generation resource. In such a case, the hydrogen storage system would have electricity-in/electricity-out functionalities.

A recent Federal Energy Regulatory Commission (FERC) order defines energy storage as "a resource capable of receiving electric energy from the grid and storing it for later injection of electric energy back to the grid."[2] FERC considers technologies that do not discharge electricity back to the grid as demand-response resources. As such, FERC and FERC-jurisdictional wholesale electricity markets will consider many alternative energy-storage technologies as demand-response resources. Moreover, it may not be clear how the example of a hydrogen storage system that switches between injecting electric energy back to the grid and using stored hydrogen for other purposes (e.g., direct-process heat fuel) would be classified.

On the other hand, in a decision surrounding the state's energy storage mandate,[3] the California Public Utilities Commission (CPUC) adopted an expansive definition of energy storage. The CPUC included, among the defining characteristics of energy storage, an ability to "store thermal energy for direct use for heating or cooling at a later time in a manner that avoids the need to use electricity at that later time." This definition appears at odds with that given by the FERC.

These definitional questions have important legislative, policy, and regulatory implications. Providing guidance on streamlining these definitions, especially as energy storage is being established, would help to avoid dichotomous treatment of technologies at the state and federal levels and within different jurisdictions of the United States. Some definitions of energy storage have a focus on technical characteristics of the underlying device. It may be prudent to "rethink" the definition of energy storage in terms of the services that a device (or set of devices) can provide instead. For instance, a combination of flexible generation and flexible loads may be capable of providing exactly the same services as energy storage (e.g., as a form of synthetic energy storage). Classifying a synthetic energy storage as energy storage as opposed to another type of device (e.g., generation and demand response) can have important and practical regulatory and policy implications.

4 Recommendations

In a world of rapidly advancing technologies, it is difficult for individuals, companies, policy makers, legislators, and regulators to know what advances are most appropriate to address energy-related needs. For example, increased loading on transmission or distribution equipment traditionally may be addressed by equipment upgrades. However, technologies such as energy storage, distributed energy resources, demand response, or other advanced control systems may be viable alternative solutions. The types of emerging energy-storage technologies that are summarized in this document fall into a class of possible solutions that are often overlooked.

Recommendation #1: The DOE should encourage the use of a screening tool.

The DOE has the expertise and exposure to real-world issues that may allow it to produce and encourage the use of a screening tool or process to identify cost-effective solutions that employ energy-storage, demand-response, or other technologies, including the ones that are outlined here.

Opportunities exist in:

1. building efficiency;
2. electricity-distribution upgrades;
3. electricity-transmission upgrades;
4. area heating and cooling; and
5. use of chemical storage for industrial and other processes, chemical feedstocks, or electricity production.

Recommendation #2: The DOE should update guidance documents.

The DOE and related government entities share an existing portfolio of guidance documents that address many of these issues.[4] The EAC suggests that the DOE evaluate the benefits of updating some of its existing guidance documents, which are already actively used by industry, or suggesting updates for documents that are not owned by the DOE. This update should include a specific "checklist" of what energy-storage technologies are appropriate to consider under different circumstances. These updated documents should be targeted to policy makers, legislators, and regulators to ensure that these stakeholders fully understand the potential benefits of these technologies to facilitate coordination between the various sectors.

Recommendation #3: The DOE should ensure consistent definitions across agencies.

The DOE could serve as an unbiased arbiter of how to classify technologies, ensuring that the definitions of energy storage, demand response, flexible generation, and other technologies are clear and consistent across federal and other regulatory agencies. Unclear or inconsistent definitions create challenges with respect to market, policy, and regulatory treatments of different assets and services. The DOE should survey how technologies have been treated in the past and, consistent with the existing FERC definitions, develop a framework for distinguishing demand response, energy storage, and other technologies from one another, providing guidance to harmonize definitions. Furthermore, the DOE may wish to consider the extent to which energy storage is defined based on the services that a particular technology can provide, as opposed to its technical characteristics.

Recommendation #4: The DOE should revise efficiency guidelines and metrics

The DOE should examine the value of integrated energy efficiency within the context of federal energy efficiency ratings and regulations, such as the Energy Star Process Rule. Energy-storage devices used for load shaping are inherently less efficient than their non-storage equivalents because of energy losses. However, their ability to change the timing of energy consumption may provide benefits that outweigh this lower efficiency. A process to value the economic and environmental impact of energy consumption at different times should be developed and applied to Energy Star ratings.

References

[1] EAC. 2017. *High Penetration of Energy Storage Resources on the Electricity System*; EAC. 2016. *2016 Storage Plan Assessment*; EAC. 2013. *A National Grid Energy Storage Strategy*.

[2] FERC, Order 841 on Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators, Docket Nos. RM16-23-000 and AD16-20-000.

[3] CPUC, Decision 14-10-045 on Decision Approving San Diego Gas & Electric Company, Pacific Gas and Electric Company, and Southern California Edison Company's Storage Procurement Framework and Program Applications for the 2014 Biennial Procurement Period, Applications 14-02-006, 14-02-007, and 17-02-009.

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Appendix A – Thermal Storage

1. Direct load control of resistive electric water heaters: These control systems ensure that water is heated when electricity is inexpensive and delivered to showers, dishwashers, and other uses on-demand from a storage tank. More sophisticated systems can provide fast-response services to the grid, including voltage support and frequency regulation. Pilot-scale programs of resistive electric-water-heater control in individual buildings exist in Hawaii, Minnesota, and Maryland. Test systems are also being deployed in Québec, Canada. Full deployment of this option is seen in France and Australia. Large-size hot water storage systems also have been deployed in Sweden for district heating systems.

2. Direct load control of electric heat pump water heaters: These systems use one-third as much electricity as resistive electric water heaters and have sizable storage tanks. Even with this lower level of energy use, heat pump water heaters can be controlled to shift water-heating loads to periods of time with low demand and energy prices. This option remains experimental, but both individual residential-scale heat pump water heaters and multi-dwelling unit CO_2 heat pump water heaters can be installed with adequate storage to enable operations to be concentrated into low-cost periods while meeting consumer demand.

3. Chilled-water storage: This is a mature technology for large campus facilities, such as universities and other district cooling systems. To date, only a small percentage of candidate sites that are appropriate for chilled-water storage have large-scale storage facilities.

4. Ice storage: This is also a mature technology that is deployed globally for large central-chiller systems which are common in large commercial buildings such as office towers and major hotels. While more expensive to build and maintain than chilled-water storage, the land area required by ice-storage systems is an order of magnitude lower. Currently, only a small fraction of candidate facilities that could accommodate ice-storage systems have one installed.

5. Chilled energy storage for inlet air cooling: This technology uses chilled thermal energy storage, which can take the form of either chilled water or ice storage, to cool inlet air for a variety of industrial processes. A common example includes cooling inlet air for combustion turbines.

6. Heat pump/borehole: Borehole thermal energy storage is a technically demonstrated technology for season-scale thermal energy storage. The technology relies on a geologic reservoir that is created to store heat. Typically, the geothermal reservoir is heated using solar collectors or chilled using air heat exchangers. The large size and environmental requirements of solar collectors and air heat exchangers limit the applicability of this technology. However, replacing collectors with heat pumps allows for the use of borehole thermal energy storage in a wider variety of use cases. Perhaps most significantly, if coupled with heat pumps, boreholes could be used in urban environments where energy storage is a valuable way to defer energy infrastructure upgrades and reduce energy use for space conditioning. While a number of borehole thermal energy storage systems have been deployed globally, the technology is not yet a standardized commercial offering.

7. Ceramic bricks: Originally developed in the 1920s, this technology uses an electrical heating system (typically either resistance heaters between the bricks or direct-contact electrodes) to

store heat in high-temperature, ceramic bricks (which are also known as firebricks). Such systems have seen deployment in New England. Stored heat can then be discharged using an air blower system for direct industrial or space-heating applications or coupled to an air-Brayton power cycle for electricity production.

8. Molten salt: This technology uses molten salts to store heat at relatively high temperatures. This heat can be pumped to a steam generator to create electricity, and it is especially suitable in combination with thermal solar plants. This technology has been installed in California and Spain.

9. High-temperature phase-change materials: High-temperature phase-change materials, especially those with valuable material properties, have been used for commercial applications of thermal energy storage. Molten silicon, for example, has a phase-change temperature of over 1400^{o} C and an energy density of more than 1 MWh per cubic meter. As such, molten silicon thermal energy storage systems allow residential customers to store a month of thermal energy for heating in a form factor that is comparable in size to a clothes washing machine. Such high-temperature materials offer potentially greater value for serving high-temperature industrial heat loads.

10. Space heating: These systems use a variety of storage media, including ceramic bricks (*cf.* Technology #7) and phase-change materials, to reduce or shift energy consumption. Some designs use low-temperature phase-change materials, which can be charged using a heat pump as opposed to a resistor.

Appendix B – Chemical Storage

1. Hydrogen (H_2): Hydrogen created by water electrolysis can be stored for later use as a feedstock for ammonia and other chemicals, as well as a direct-process heat fuel. Stored hydrogen can be recombined with oxygen in a fuel cell or combustion turbine to generate electricity, which would make the resulting storage cycle more similar to an electricity-in/electricity-out system. Electrolysis also produces oxygen as a byproduct. This oxygen can be used for industrial or other purposes. However, using hydrogen is hazardous, and it is difficult to store and expensive to transport. Therefore, co-locating a hydrogen storage system with a source of charging energy (e.g., a large wind or solar facility) can avoid transportation and power system-interconnection costs. Such a co-location strategy could result in a hybrid energy storage system that in many ways has the operating capabilities and characteristics of a highly flexible generation resource. In such a scenario, the hydrogen storage system would have both electricity-in and electricity-out functionalities.

2. Ammonia (NH_3): The ammonia molecule is composed of three hydrogen atoms that are bonded to one nitrogen atom, making it large enough to be stored in a conventional tank and transported by conventional pipelines. However, ammonia is highly poisonous, so extensive safety controls are paramount. Ammonia can be used as a fuel in conventional power plants, but its resulting nitrogen oxide emissions are an important consideration. There are currently thousands of miles of ammonia pipelines in the United States, which are mostly used for transporting fertilizer feedstocks from producing states near the Gulf of Mexico to the agricultural centers of the Midwest. Two uses of ammonia-based energy storage are attractive for further consideration. The first uses low-cost or variable renewable energy to meet existing demand for ammonia-based fertilizer. The second produces additional ammonia for use as a fuel for transportation, industrial process, or electricity generation.[5]