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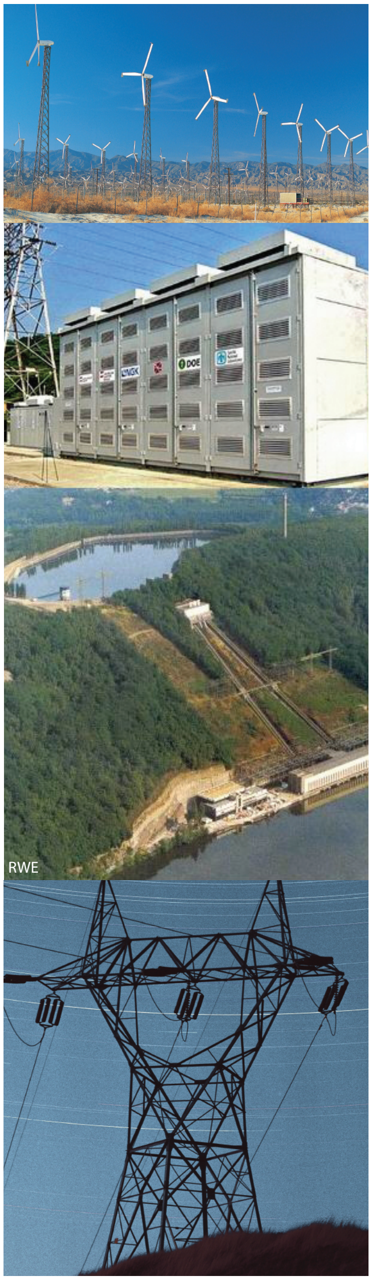

Energy Storage for Low-carbon Electricity

January 2009

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TOWARD A LOW-CARBON ELECTRICITY SECTOR
CCPP Technology Policy Brief Series

Energy Storage for Low-carbon Electricity

POLICY BRIEF

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Climate Change Policy Partnership
Duke University
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Series Overview:

Toward a Low-Carbon Electricity Sector

This paper is one in a series by the CCPP at Duke University to explore the barriers facing large-scale, low-carbon electricity generation and increased efficiency in the near-term – primarily the next ten to fifteen years. Policy drivers may be necessary to provide the right price signal to develop low-carbon emission technologies, but a price signal alone may not be enough to enable broad-scale deployment.[1] Significant technical, legal, infrastructural, and social barriers prevent the implementation of the necessary technologies and efficiency improvements.

The series provides an overview of the barriers and outlines general policy options for lawmakers who wish to speed the development and/or wide-scale deployment of low-carbon energy technologies. It will include papers focusing on specific energy generation technologies, including renewable energy and energy storage, and energy efficiency, a cost-effective near-term option for displacing carbon-intensive energy generation.

Acknowledgments:

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[1] Policy drivers are under consideration include a nationwide cap-and-trade system for greenhouse gas (GHG) emissions, regulation of GHGs emissions under the Clean Air Act, expanded action on the state and regional levels, or some combination thereof.

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I. Executive Summary

Energy storage is an important enabling technology for a low-carbon electric power system, as most low-carbon energy technologies cannot flexibly adjust their power output to match fluctuating demand. Many energy storage technologies exist today which could be coupled with renewable energy, nuclear, or coal-fired power with carbon capture and storage to provide dispatchable electricity. However, the deployment of energy storage technologies faces many barriers. If policymakers address the challenges of developing and deploying energy storage, they may facilitate the transition to a low-carbon electricity system.

This policy brief reviews existing energy storage technologies and highlights their potential and limitations for enabling low-carbon energy sources. It also discusses the barriers inhibiting implementation of storage technology today. Some of the barriers are overarching for all energy storage technologies; others are unique challenges associated with individual technological options. Finally, specific policy options for overcoming these barriers are considered.

Research, development, and demonstration of promising energy storage technologies are critical to move forward. Specifically:

- The U.S. federal government’s research and development funding for energy storage is grossly insufficient.
- Incentives are needed to encourage the private sector to invest in technology advancement and commercialization of promising technologies.
- Pumped hydro-storage has the most proven track record, but it requires an updated assessment to evaluate its remaining potential.
- Compressed-air energy storage and rechargeable battery technology hold great potential, but each requires substantial support to realize this potential.
- A smart grid which incorporates energy storage would address numerous limitations facing the power industry and position the United States to face mounting energy challenges.
- Research and development may bring about revolutionary breakthroughs to enable innovative energy storage technologies.

Grid energy storage sits on the boundaries of generation and transmission. Its pivotal role in a low-carbon electricity system is not sufficiently understood and appreciated. Despite its tremendous importance, energy storage has yet to obtain a priority status in the national policy agenda. With this paper, we hope to contribute a step in the right direction.

II. Introduction

Recently, Congress has considered numerous proposals to cap greenhouse gas (GHG) emissions through market-based cap-and-trade systems. If enacted, a mandatory cap-and-trade system would create a price signal for GHG emissions and would likely cause electric power generators to adopt low-carbon technologies. Renewable energy, nuclear power, and coal-fired power with carbon capture and sequestration (CCS) are the major options for low-carbon electricity. These technologies, though, have limitations within an electricity market. Electricity demand varies constantly, and supply technologies must adapt in real time. Many promising renewable energy technologies, such as wind and solar, can generate only when the resource is available. Nuclear and CCS are designed to run almost all of the time and cannot adapt to constantly changing demand. The best low-carbon options collectively will not provide for a robust electricity system without the ability to store energy when it is produced in excess and to release energy when demand peaks.

Energy storage is an enabling technology for low-carbon electricity

Wind power and solar generators have little control over the timing of generation. The intermittent and nondispatchable nature of these sources pose severe disadvantages for the competitiveness of wind power or solar in the electricity market and may limit their ultimate expansion. Energy storage is one of the most promising solutions to both intermittency and indispatchability. Indeed, energy storage is potentially a complete solution to the grid integration of wind power or solar. If a wind farm is coupled with an energy storage facility, it can provide stable output and, more importantly, it can dispatch the output at times with the highest demand (Lee and Gushee 2008).

Energy storage may not only enable full deployment of renewable electricity, but it may also serve important functions in a nuclear- and/or CCS-dominated power system. Nuclear and coal with CCS offer large-scale stable base-load[1] output, but are unable to adapt to fluctuant demand. Building enough of these base-load units to meet peak demands would be prohibitively expensive and wasteful. The variable peak demand has traditionally been served by inexpensive but inefficient and carbon-intensive

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[1] Power plants may be divided into two basic types: base-load and peak-load. Base-load power plants have high capital costs and low operating costs. Utility planners typically build only enough base-load power so that their base-load units can run almost all the time. Because demand peaks last only a short time, to meet peak demand, utilities build units that have a low capital cost and high operating cost, knowing that these units will be needed for only short periods of time and can be turned off when demand drops. The prices of peak-load electricity are usually several times higher than base-load prices.

natural gas- or oil-fired peaking plants that can start generating electricity very quickly. Energy storage would make it possible to marginally increase nuclear and CCS base-load capacity and store the excess electricity generated at night to use as needed during peak hours of the day.

In a carbon-constrained electricity system, energy storage can provide low-carbon dispatchable peak-load power regardless of the mix of renewables, nuclear, and CCS. In short, energy storage is an essential enabling technology for a low-carbon power system.

Many energy storage technologies exist today that can be coupled with wind power to provide dispatchable electricity. However, the deployment of energy storage technologies faces many barriers. Some of the barriers are overarching for all energy storage technologies; others are unique to a particular technology. These barriers are discussed in later sections.

Stored renewable electricity can be used to meet both base-load and peak-load demands. Because peak-load power has a higher price than base-load power, it is reasonable to expect that renewable-plus-storage operators will sell their outputs as peak-load first. In the future, if wind power expands beyond peak-load demand, it may also serve as base-load power.

The storage technologies for renewable energy may evolve from existing grid-tied energy storage technologies. Currently, commercial applications of grid-tied energy storage are divided into two functions: power quality (PQ) and peak-shaving[2] (PS). PQ energy storage prevents momentary (seconds or minutes) outages, which could be a concern with large-scale integration of wind or solar into the grid as the strength of the wind or amount of cloud cover could cause intermittent drops in energy output (EPRI PEAC Corporation 2004). PS energy storage stockpiles excess low-value, off-peak power (usually for hours) and feeds it back into the grid as high-value peak-load power. In existing markets, PQ is a higher-value service than PS.

A system approach is required

Experts in wind power integration recognize that power producers cannot effectively manage the variability of wind power output in isolation, as it is the grid system rather than an individual wind farm that needs to be balanced (Smith, et al. 2007). Grid systems historically employ PS and PQ facilities to enhance their capacity in handling variable loads. As a grid system's general capacity in managing variability increases, its ability to accommodate more renewable energy will increase accordingly. It does

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[2] A.k.a. load leveling.

not matter whether these PS and PQ facilities were originally intended as storage for renewable energy per se, nor does it matter whether these facilities were located side-by-side with renewable power generators. As long as the overall PS and PQ capacities expand, the grid system will be able to accommodate more renewable energy. Therefore, in order to accommodate more renewable energy in the grid, PS and PQ energy storage should be encouraged regardless of the original purposes for which they were intended.[3]

In addition to being an essential enabling technology for a low-carbon power system, energy storage brings about many other benefits. It improves the reliability of the power system and enhances the flexibility of grid operation. Energy storage in many places could be an effective substitute for transmission upgrades.

Currently, there are three commercially available energy storage technologies—pumped hydroelectric storage (PHS), compressed-air energy storage (CAES), and sodium-sulfur (NaS) battery technology—that meet the PS/renewable energy storage technical requirements. However, each of these commercial options faces barriers in expanded deployment. Other storage technologies are being developed. Some technologies currently employed only for PQ functions may also be re-engineered to store renewable energy (Mears, Gotschall and Kamath 2003) (Schaber, Mazza and Hammerschlag 2004) (Baxter 2006).

III. Barriers

A. Low research and development support

Many promising energy storage technologies are still in the developmental stage. Scientific breakthroughs may enhance their performances and reduce costs. Revolutionary new materials and chemical processes may also enable novel energy storage technologies. To exploit the potentials for technological innovation, substantial investment in research and development is required.

The Department of Energy (DOE) has maintained an R&D program on energy storage for the past two decades. The program is very small, however, generally receiving annual funding of a few million dollars—a trivial amount compared to the R&D budgets for fossil energy, nuclear power, or renewable energy (Lee and Gushee 2008). Investment in R&D could bring about revolutionary new materials and

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[3] The original intention behind most existing PS facilities is power arbitrage (buy low-price base-load power, store and sell it at high-price peak hours) rather than renewable power storage. The original intention behind existing PQ facilities is preventing disruptions in general rather than disruptions caused by renewable power per se.

chemical processes to enable innovative energy storage technologies.

Table 1: DOE R&D Budget[4]

(Millions of dollars)

Funding category	2005 actual	2006 actual	2007 actual	2008 preliminary	2009 proposed
Energy efficiency and renewable energy	533	428	921	1,176	1,019
Nuclear energy	82	93	300	441	630
Fossil energy	469	415	469	563	620
Energy storage	2	2	3	2	2

Two national laboratories are involved in energy storage research.[5] The Sandia National Laboratories manages the Energy Storage Systems (ESS) Research Program, which encompasses the majority of the energy storage R&D in DOE. Congress has earmarked most of the funding for specific demonstration projects, with little remaining for basic research (Boyes 2006). In recent years, funding limitations have forced the DOE energy storage system program to abandon most of its basic research and focus primarily on demonstrations in partnership with state agencies or utilities. These projects are mainly demonstrations of near-commercial technologies. The Oak Ridge National Laboratory (ORNL) is developing an energy storage program that would mainly focus on fundamental scientific research for advanced batteries and electrochemical capacitors.[6] The ORNL program is still in its formative stage.

The Energy Independence and Security Act of 2007 includes a title on “Energy Storage Competitiveness,” which instructs the DOE to implement research, development, and demonstration (RD&D) projects for energy storage systems for electric vehicles, stationary applications, and electricity transmission and distribution. The Act also establishes an Energy Storage Advisory Council and for the council to develop a five-year plan for integrating basic and applied research so that the United States retains a globally competitive domestic energy storage industry. The Act authorizes $50 million per year for the next 10 years for basic research; $80 million per year for applied research; and $100 million per year for demonstration.

The actual appropriated funding for energy storage RD&D in 2008 showed little increase, however. The budget for energy storage in fiscal year 2008 was $2 million. For fiscal year 2009, Congress passed a

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[4] Data compiled from the National Science Foundation (http://www.nsf.gov/statistics/fedbudget/) and Sandia National Laboratories.

[5] The Renewable Energy National Laboratory’s energy storage project is focused on vehicular/mobile applications rather than stationary applications.

[6] http://www.ornl.gov/sci/energystorage/.

Continuing Resolution which authorizes spending at the 2008 level. Without the necessary appropriations, the Energy Independence and Security Act of 2007 provides only symbolic support for energy storage R&D.

B. Innovation valley of death

Many promising energy storage technologies are pre-commercial. Studies on technological innovations reveal a "valley of death" in early stage commercialization (Branscomb and Auerswald 2002). Promising technologies often fail to commercialize due to the scarcity of technical experience and market information. For capital-intensive investment such as massive energy storage, buyers are typically unwilling to try technologies without good track records in performance and reliability. Many innovative technologies may achieve excellent performance in laboratories, but they generally lack operational track records in a real-world environment. On the one hand, it is impossible to build experience in commercial operation before the developer can sell the technology for commercial applications. On the other hand, it is very difficult to sell an innovative technology before it has accumulated good records in commercial operation. Real-world conditions can be difficult to simulate in laboratory tests, and projects often require a great deal of tune-ups and incremental engineering to make them ready for commercialization. For any first-of-a-kind technology, the buyer must bear a high risk. The first movers' experiences will benefit all followers. In other words, the first movers may produce a public good, suggesting that government subsides during the early stages of deployment may be appropriate. For large-scale capital-intensive technologies, early commercialization stages may last for a very long time. As exemplified in the case of compressed-air energy storage in a later section, the early commercialization stage has lingered over four decades.

C. Unrecoverable transmission benefits

Grid energy storage technologies can improve the efficiency, reliability, and security of the electricity transmission grid. However, transmission operators generally regard energy storage as power generation rather than as a transmission upgrade. They usually do not allow the cost recovery for the application of energy storage technologies as part of, or in lieu of, investment in transmission upgrades. Section 1223 in the Energy Policy Act of 2005 (EPACT) directs the Federal Energy Regulatory Commission (FERC) to encourage "advanced transmission technologies," including energy storage (42 U.S.C. §16422). In February 2007 the FERC issued Order 890, which mandated that all Independent System Operators (ISOs)[7] change their market tariffs to allow nongeneration resources (such as energy storage) to bid and

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[7] An ISO coordinates, controls and monitors the operation of the electrical power system, usually within a single state, but sometimes encompassing multiple states.

sell into frequency regulation[8] markets. The ISOs are undergoing rule change processes to comply with Order 890. For example, the Midwest ISO (MISO) filed a request to create an entirely new regulation resource category—Stored Energy Resources (SER) on April 25, 2008. Although the rule changes are moving in constructive directions, they have not yet entirely removed barriers to comparable treatment of energy storage resources. For example, small, diverse grid-tied energy storage devices also contribute to the stability of the grid, but they are unlikely to bid in the frequency regulation market. A recent FERC ruling in March 2008 also denied a request from the Lake Elsinore Advanced Pump Storage project "to be operated and/or managed . . . or functionalized as transmission for rate recovery purposes." Although there are some positive rule changes that allow a specific subset of energy storage technologies to participate in frequency regulation market, most energy storage investors are still unable to recoup their contributions in improved power quality, enhanced grid reliability, and avoided transmission upgrades. Further rule changes may be necessary to facilitate the deployment of energy storage technologies.

D. Difficulties in existing niche market

In the near term, energy storage technologies will likely commercialize only for their PQ or PS services. PQ is already a profitable market for a range of energy storage technologies. Unfortunately, few PQ technologies can be easily adapted to store renewable electricity due to their short durations.[9] PS technologies, on the other hand, largely meet the technical specifications required for storing intermittent renewable electricity. Furthermore, if PS facilities are increasingly installed on the power grid, the power grid's capacity in accommodating renewable energy will improve accordingly. Therefore, the PS market may serve as a niche market for incubating energy storage technologies for renewable energy. However, there are significant barriers for energy storage technologies in the PS market.

A PS storage facility generates revenues by power arbitrage. It usually requires heavy upfront capital investment. The costs can only be recovered over decades. The heavy capital requirement poses a stringent entry barrier for investors.

Although the PS market may serve as an incubator, there is no significant near-term environmental benefit in power arbitrage/peak-shaving. The lion's share of existing base-load power capacity is coal-fired, followed by nuclear. The stored electricity, when it is released during peak hours, is mainly competing with gas-fired electricity. In short, in the near-term, storage facilities may be replacing gas-fired power with coal-fired power in most cases and with nuclear power in others. Because coal-fired

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[8] Frequency regulation is an ancillary service for PQ. The service is to correct for unintended fluctuations of up to a few minutes in generator output.

[9] Batteries may be designed to serve PQ/PS dual purposes with some penalties in efficiencies and service lives.

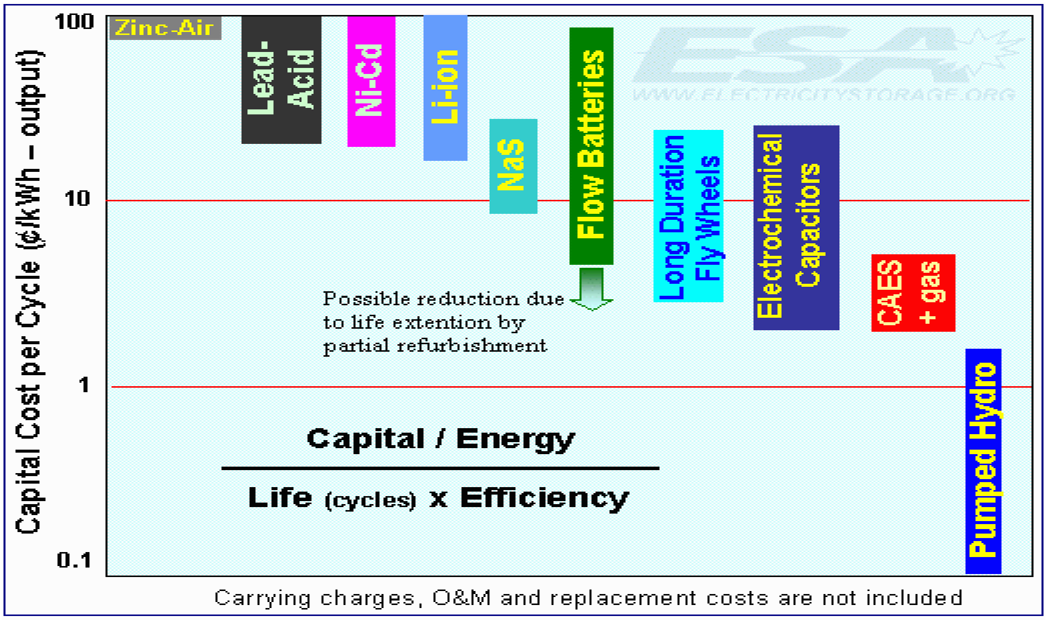
power emits more carbon than gas-fired power, if a PS facility used coal-fired base-load power to replace gas-fired peak-load, carbon emissions would increase. If a PS facility replaces gas-fired power with nuclear power, carbon emissions would decline.

IV. Technological Options

This section briefly introduces major technological options of grid energy storage. A more detailed discussion of these technologies is in the appendix. Pumped hydro storage (PHS) has been widely used worldwide as well as in this country since the 1930s. Only two compressed-air energy storage (CAES) facilities (one in Germany, the other in the United States) are currently in commercial operation. Sodium-sulfur (NaS) batteries are commercially available from the Japanese Company NGK Insulators Ltd. They have been installed in many places mainly for PQ purposes but are increasingly considered for PS purpose as well.

Flow batteries, flywheels, superconducting magnetic energy storage, and electrochemical capacitors are currently used only for PQ purposes. Hydrogen energy storage is still in the developmental stage. Each of the technologies has its own strengths and weakness. There is unlikely to be one single winning technology in energy storage. The technologies may compete against each other in some places but complement each other in other cases.

Figure 1: Cost Comparison of Energy Storage Options[10]



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[10] http://www.electricitystorage.org/tech/technologies_comparisons_percyclecost.htm.

A. Pumped hydro storage (PHS)

Pumped hydro storage is the only large-scale energy storage technology in widespread use. It uses off-peak power to pump water uphill to an elevated reservoir. At peak hours, the water is released to flow to a lower reservoir, and the water flow drives turbines to generate electricity. There are many ways to design PHS systems. The lower reservoirs can be lakes, rivers, underground caverns, or oceans. The upper reservoirs can be any elevated geological formation capable of holding significant amount of water. PHS is available at almost any scale with discharge times ranging from several hours to a few days. With over a 70-year history of commercial operations at hundreds of locations worldwide, PHS is undoubtedly a mature technology. The round-trip efficiencies are in the range of 60% to 85%.[11]

PHS plants are characterized by long construction times and high capital expenditure. Although its life-cycle cost is low, the initial capital cost remains a tremendous challenge for investors. Existing PHS capacity in the United States is 21.8 GW (DOE/EIA 2008). Conventional wisdom suggests that the United States has run out of economically and environmentally feasible sites for PHS. This conventional wisdom, however, is not based on a comprehensive assessment. Because PHS may be the least-cost energy storage, disregarding this option without an updated assessment would be imprudent. A recent estimate suggests that at least 78 GW of PHS may be developed at existing reservoirs (Bishop 2008).

The federal government (Army Corps of Engineers, Bureau of Reclamation, and Tennessee Valley Authority) is the largest owner of hydroelectric capacity in the United States, and as such, it may be well-positioned to develop new PHS projects. PHS may present an opportunity if the U.S. federal government wishes to develop energy storage capacity directly.

B. Compressed-air energy storage (CAES)

Compressed-air energy storage uses off-peak electricity to compress air into an underground air-storage vessel (air-tight caverns or mines). At peak hours, the pressurized air is fed into a gas-fired turbine to generate electricity. Although CAES is not widely employed, it is generally believed to be commercially viable.

Currently there are only two operating CAES systems in the world. The first commercial CAES was built in Germany in 1978; the second was built in the United States in 1991. Since then, many attempted CAES projects in various parts of the world have failed. Two ongoing projects in the United States have also

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[11] The wide range is due to the fact that some old facilities are equipped with outdated equipment. It is possible to renovate old facilities to increase capacities and efficiencies.

been postponed several times. Although some studies indicate great potential in CAES, the technical and financial difficulties in developing CAES facilities remain challenging. Further financial support may be needed for the deployment of CAES.

C. Rechargeable batteries

Rechargeable batteries store electricity in chemical energy. The most promising types include sodium-sulfur (NaS) batteries and flow batteries. The advantages of battery storage include high efficiency, relatively compact size, and flexible location. The main constraint is their high cost. Another disadvantage of batteries is that they often suffer from memory effect.[12] Their lives are in the range of 10 to 15 years—significantly shorter than those of PHS and CAES. For momentary (seconds or minutes) outage mitigation, some batteries are already commercially competitive. However, for large-scale storage (hours), batteries usually cost more than an order of magnitude more than PHS on the basis of per recharge cycle and many times higher than CAES.

For batteries to serve as storage of renewable energy, the costs must be further reduced. If there were a sustained demand for the technology, such cost reduction could be achieved through technological learning and economies of scale. There is a “chicken-and-egg” dilemma: the technology will not become cost-effective unless it gradually goes down a learning curve with sustained demand over decades, but there will not be a sustained demand if the technology is not already cost-effective. A policy mandate to create the demand may be a way to overcome the chicken-and-egg dilemma.

D. Flywheels

A flywheel stores electric energy in the form of mechanical inertia. An electric motor accelerates a rotating disc to charge the energy. The motor acts as a generator in reverse, slowing down the disc and producing electricity. Flywheels are suitable for frequent discharge and require little maintenance. Due to flywheels’ longer lives, their life-cycle costs could be lower than those of batteries. Flywheels are made of inert (nonhazardous) materials and can operate in harsh operating environments (Mears, Gotschall and Kamath 2003). They are free from memory effects and are capable of very frequent recharges. The major challenge is to reduce standby power losses in order to produce long-duration flywheels. Further R&D efforts are required.

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[12] Memory effect is an effect observed in rechargeable batteries that causes them to gradually lose capacity over time.

E. Superconducting magnetic energy storage (SMES)

A superconducting magnetic energy storage system stores energy in a magnetic field created by the flow of electric current in a superconducting coil. The superconducting coil must be cryogenically cooled below its superconducting critical temperature. When SMES technology was originally conceived in the early 1970s, it was intended as a large-scale energy storage technology (Baxter 2006). However, high capital costs hindered the commercialization of large SMES. Since mid-1990s, the focus of development has shifted to PQ-function devices because they are smaller and therefore cheaper to build. There are several small SMES units in commercial use for PQ. Further RD&D would be needed to develop and commercialize large-scale SMES.

F. Electrochemical capacitors

An electrochemical capacitor stores energy in electrostatic charges on opposite surfaces of the electric double layer (Baxter 2006). Compared to batteries, electrochemical capacitors have lower energy density but they are capable of more (tens of thousands) and frequent cycles. They are also capable of fast response. The round-trip efficiency is about 80–95%. Because the duration of discharge is very short, electrochemical capacitors are only suitable for PQ purposes.

G. Hydrogen

A hydrogen energy storage system uses electricity to electrolyze water into hydrogen and oxygen. The generated hydrogen is stored until electricity is needed, at which time a fuel cell or internal combustion engine uses hydrogen to generate power and feed it back to the grid. Hydrogen technology is extremely clean. Neither the production (through electrolysis) nor the usage of hydrogen produces any pollutant. Hydrogen energy storage is widely discussed but has not yet any commercial application.

The National Renewable Energy Laboratory conducted a study on wind-battery-hydrogen integration (Fingersh 2004). The study concluded that even if the capital costs of the electrolyzer and fuel cell were both reduced to zero, a hydrogen energy storage system could not compete with a battery due to its low efficiency. This efficiency gap may be insurmountable without revolutionary breakthroughs for hydrogen storage systems.

H. Smart-grid-enabled diverse energy storage

There are technologies that sit on the boundary of energy storage and load-shifting. Currently, such systems are commercially available, but their operation is not dynamic enough to match the intermittent pattern of renewable energy output. Smart grids are advanced power transmission systems equipped with intelligent, distributed, and highly-adaptive control systems, which could enable the dynamic operation of a diverse and interconnected system of energy storage and demand response resources. Demand response resources are load-shifting measures that do not store energy, but could still respond to intermittent power. Policymakers may facilitate the deployment of smart grids and load-shifting technologies to take advantage of diverse energy storage and demand response resources.

V. Policy Options to Address Barriers to Energy Storage

As federal policymakers tackle the problem of climate change, they may determine that it is important to remove some or all of the barriers preventing the expansion of the nation's energy storage capacity. Doing so could provide a means to (1) store excess power from wind and solar facilities and other low-carbon power plants, thereby allowing the overall percentage of power from these sources to expand; (2) provide back-up power from other sources to cover energy needs if the amount of wind or solar generation dips during peak hours; and (3) improve the overall stability and reliability of the power grid. The section outlines policy options for addressing the barriers. The options are drafted so they could be pursued one-by-one or as a group. They are divided into two major categories—supply-push and demand-pull—as experience with other technologies suggests that both supply-push and demand-pull are needed to promote technological development (Norberg-Bohm 2000).

A. Supply-push policy/research, development, and demonstration

Increase basic research funding

The DOE has assembled panels to identify basic research needs for electrical energy storage (Office of Basic Energy Sciences 2007). The panels identified chemical energy storage devices (batteries) and electrochemical capacitors as the two most promising areas. Regarding batteries, the panels singled out recent developments in nanostructured and multifunctional materials as having the potential to dramatically increase battery performances. For electrochemical capacitors, new materials are the main focus for further research. The development of tailor-made nanostructured high-surface-area electrodes offers great potential for improving the performance of capacitors. Nanostructured materials and innovative electrolytes are cross-cutting research directions in electrical energy storage.

Although the DOE has identified research targets for energy storage, it provides very little funding to conduct R&D, which requires substantial financial resources. The current level of funding is obviously insufficient. In order to generate scientific breakthroughs, a substantial increase in R&D funds will likely be necessary.

Improve management of basic research

Governments have poor track records of picking winning technologies. For technologies in which the government does not have a direct procurement interest, clientele-oriented R&D support may be a good approach to ensure that the choices of technologies are market-oriented and free from politically determined objectives (Nelson and Langlois 1983). Clientele-oriented support allows the recipients of R&D funds to set their goals in a market-driven and efficient manner. Currently, Congress typically earmarks the majority of the DOE's energy storage R&D funds. A competitive process for clientele selection with clientele-oriented R&D support may be a more effective mechanism in managing R&D funds. Public-private partnership is also an established model for clientele-oriented R&D supports.

Encourage private investment in applied research

After basic research brings about technological breakthroughs, it will still require a great deal of applied research to develop technologies into working devices. The private sector is usually the primary investor in applied research because companies want to obtain proprietary data and patents from applied R&D. However, private investors will not invest in R&D unless they are convinced of the demand for the technology. Therefore, in order to encourage significant private investment in applied R&D for energy storage, policymakers must foster the demand. In addition to acting as a technology incubator, demand-pull policy options discussed in the next section may also serve the purpose of encouraging private R&D investment.

Increase financial supports for demonstrations of pre-commercial technologies

The Sandia National Laboratories' ESS program collaborates with the California Energy Commission (CEC) and the New York State Energy Research and Development Authority (NYSERDA) in demonstration projects including super capacitors, zinc-bromine batteries, sodium-sulfur batteries, lead-acid batteries, and flywheels. Increasing financial support for these efforts would facilitate the commercialization of promising technologies.

Federal/state/utility collaboration is a good approach in bridging the valley of death between innovation and the marketplace. The cost-sharing scheme is an incentive to pursue only practical technologies. If the government funds the entire cost of a demonstration project, it increases the risk that the project may pursue politically preferred but technically impractical choices. In addition to cost-sharing, state and utility partners bring in important knowledge and expertise about the local regulatory environment, market conditions, and operational practices. Currently, due to budget limitations, the scale and scope of demonstration projects are very limited. In order to facilitate early-stage commercialization of promising technologies, Congress could substantially expand the demonstration efforts.

Loan guarantee for large-scale energy storage demonstration projects

Difficulties in financing have hindered the development of some large-scale energy storage projects. (Examples include Norton CAES (Global Power Report 2002) and Lake Elsinore PHS (Burgin 2007)). Although these projects maybe financially justifiable in the long-term, the tremendous upfront capital costs (billions of dollars) is a formidable barrier. The Energy Policy Act 2005 authorized loan guarantees for “innovative technologies” that avoid greenhouse gases, but did not allow energy storage technology to qualify for the loan guarantees (42 U.S.C. §16513). Energy storage technologies indirectly avoid greenhouse gases by enabling carbon free energy technologies such as nuclear and wind power. Providing loan guarantees to large-scale (i.e., > 1 GW) energy storage demonstration projects would ease the difficulties in financing.

B. Demand-pull policies/financial incentives

Production tax credits (PTCs) for stored electricity

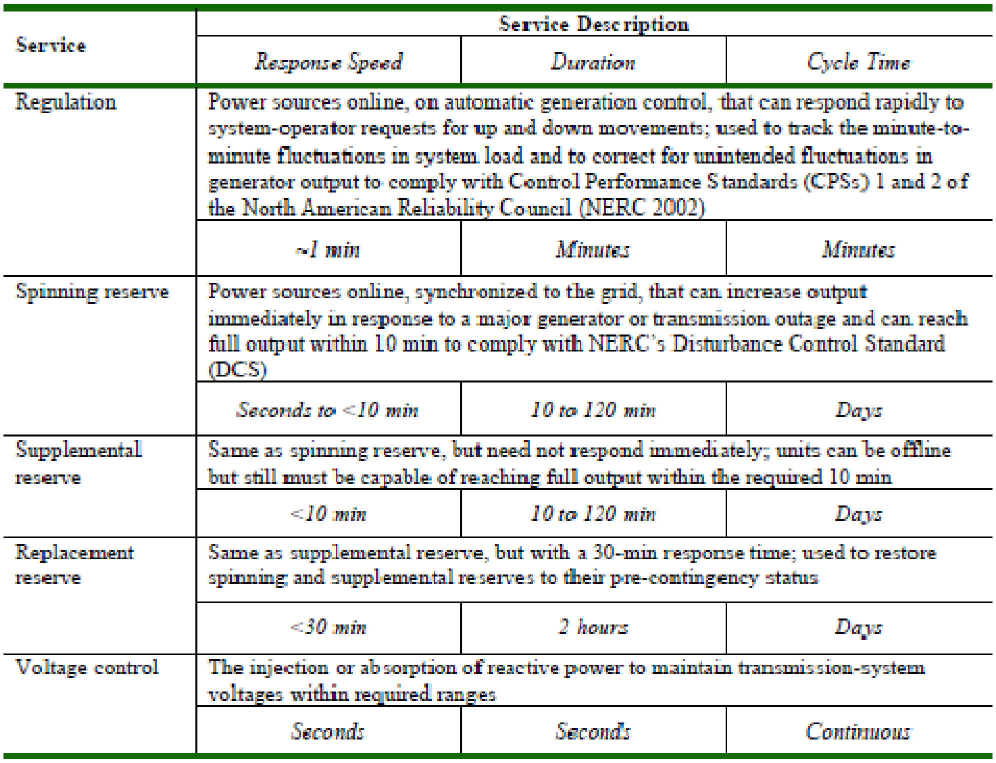
Currently, PTCs are provided to renewable power and new nuclear power, but are not available for stored electricity. Electricity storage is a strategic enabling technology in both renewable-dominating and nuclear-dominating scenarios. Congress could include stored electricity in the PTC provisions, either by directly tying the energy storage PTC to increased renewable power or by allowing any energy storage projects to qualify because of the overall effect of improving the grid’s ability to accommodate intermittent renewable energy sources.

Feed-in tariffs for stored electricity

Several countries, including Germany, Spain, and Australia, have adopted feed-in tariffs to promote renewable energy. The California Public Utilities Commission approved a feed-in tariff for renewable energy in January 2008. Currently, stored electricity is not considered renewable and does not enjoy feed-in tariffs. If a feed-in tariff were made available for stored electricity, it could provide the price stability and long-term visibility required for investment in energy storage.

Create a stored electricity reserve market

In order to maintain reliable operations of the interconnected transmission system, transmission operators have created several markets of ancillary services (Kirby 2004). Some energy storage technologies are already competitive in some of the ancillary service markets. The following table is a summary of key ancillary service markets. Regulation and voltage control services require fast responses, but only for short durations. Reserve services may require up to two hours of duration and could be satisfied with PS energy storage technologies. Existing ancillary services are not sufficient in managing the intermittency of renewable energy. For the purpose of renewable energy, the required duration is 6–10 hours. If renewable power continues to expand its market share, grid operators may find it useful to create an ancillary service market for renewable energy intermittency. Congress may instruct the FERC to develop rules for such market.



Service	Service Description		
	Response Speed	*Duration*	*Cycle Time*
Regulation	Power sources online, on automatic generation control, that can respond rapidly to system-operator requests for up and down movements; used to track the minute-to-minute fluctuations in system load and to correct for unintended fluctuations in generator output to comply with Control Performance Standards (CPSs) 1 and 2 of the North American Reliability Council (NERC 2002)		
	~1 min	*Minutes*	*Minutes*
Spinning reserve	Power sources online, synchronized to the grid, that can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 min to comply with NERC's Disturbance Control Standard (DCS)		
	Seconds to <10 min	*10 to 120 min*	*Days*
Supplemental reserve	Same as spinning reserve, but need not respond immediately; units can be offline but still must be capable of reaching full output within the required 10 min		
	<10 min	*10 to 120 min*	*Days*
Replacement reserve	Same as supplemental reserve, but with a 30-min response time; used to restore spinning and supplemental reserves to their pre-contingency status		
	<30 min	*2 hours*	*Days*
Voltage control	The injection or absorption of reactive power to maintain transmission-system voltages within required ranges		
	Seconds	*Seconds*	*Continuous*

Figure 2 Definitions of key ancillary services

C. Regulations and planning

Incorporate storage in national transmission plan

The need to overhaul the national power grid and build an electricity superhighway has become increasingly recognized as a national policy priority. There are already many plans to expand and improve the transmission system to accommodate remote wind farms. Some are calling for a National Electrical Superhighway (U.S.DOE 2003) (American Electric Power 2007) (Krapels 2008). However, most of the current proposals only consider the locations of power resources and demand centers. Some of the best storage sites (for PHS or CAES) may be remote. The grid expansion needed to connect storage sites is currently overlooked.

In addition, there may be a synergy between smart grid and energy storage. A smart grid may enable storage facilities to operate more efficiently and therefore may enhance the competitiveness of energy storage. Incorporating storage capacity into a smart grid can tremendously improve the quality and reliability of the grid. If Congress will consider a plan for a national power grid, it may consider including energy storage in the plan.

Treat storage as equivalent transmission upgrade

Storage facilities can help alleviate both the lack of transmission capacity and stability problems. However, energy storage facilities currently do not qualify for transmission pricing incentives and are not usually considered in transmission planning processes. In many cases, it may be cheaper to build energy storage facilities than to upgrade the power lines. Treating storage technologies as comparable to the expansion of traditional transmission facilities would increase the market penetration of storage technologies. The FERC could consider rules requiring that (1) energy storage be treated as comparable to traditional transmission expansion or upgrades; (2) investment in energy storage qualify for transmission pricing incentives; and (3) energy storage technologies be considered in transmission planning processes.

Relax ownership restrictions

Many states impose restrictions on the roles that customers and industries can play in power systems. For example, distribution companies are often not allowed to own generation facilities, and utilities discourage their customers to invest in services traditionally offered by utility companies. Grid energy storage sits on the boundaries of generation and transmission (APS Panel on Public Affairs Committee on Energy and Environment 2007). A law and/or FERC rulemaking to relax ownership restrictions may encourage investment in energy storage.

VI. Conclusion

Energy storage is an important enabling technology for a low-carbon power system. It also improves power quality, prevents tremendous costs of power failures, and enhances security of the grid. However, its benefits are not commonly appreciated and it has yet to obtain a priority status in the national policy agenda. Candidate technologies exist, but many face barriers that, if left unaddressed, could prevent their large-scale adoption. Policymakers could help reduce GHG emissions from the electricity sector by examining these barriers and enacting laws and/or regulations to facilitate the expansion of energy storage options.

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VIII. Appendix – Further Discussions of Selected Technologies

This appendix provides a more detailed discussion of some of the energy storage technologies. A particular focus is on the experiences of deployment and commercialization. Most assessments of technologies emphasize on the successful experiences and overlook the unsuccessful ones. Such unbalanced coverage tends to underestimate the difficulties in the commercialization of innovative technologies. In this section, cost data are only provided for commercially operating systems because cost estimates of pre-commercial technologies tend to be highly unreliable. Cost estimates of pre-commercial technologies are typically done by summing up the costs of major components and materials with a conceptual design. This approach implicitly assumes no cost with product development and commercialization. The business rule-of-thumb regarding the commercialization of innovative technologies is that for every dollar expended upon pure and applied research, 10 dollars must be expended upon development and 100 dollars are required for commercialization (Allen Consulting 2003). Therefore, it is not uncommon that an assessment of a pre-commercial technology may underestimate the overall cost very significantly, as the assessment does not include the costs of development and commercialization.

A. Pumped hydro storage (PHS)

PHS plants require long construction times and high capital expenditure. Although the operation and maintenance costs are low, it would still take decades to recover the initial capital costs. The life of the facility is limited by its license (usually 40–50 years) rather than technical durability, but license extensions are possible. Investors typically evaluate a project with the expected capital recovery over a remaining life under an existing plant license (Mischkot 2006). The possible revenue from renewed license life is usually not considered in investment decisions for hydropower (including PHS) project.[13]

The peak construction period for PHS facilities in the United States stretched from the 1960s through the 1980s. Very few facilities have been built since 1990. Current U.S. PHS capacity is 21.8 GW (DOE/EIA 2008). Conventional wisdom suggests that the United States has run out of economically and environmentally feasible sites for PHS.

The belief that PHS has reached a plateau is not based on a comprehensive assessment of its potential. Assessments in the 1970s and early 1980s invariably indicated tremendous PHS potentials in this country. The most comprehensive assessment of PHS potential was published in 1982 by the Army Corps of Engineers. This report suggested that there are widely available sites throughout most parts of the country with total potential capacity of over 1,000 GW (U.S. Army Engineer Institute for Water Resources 1982). No new comprehensive assessment of PHS potential has been undertaken since 1982 (Bahleda

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[13] Even if investors consider the revenues beyond the first license life, the discounted present value of revenues in such remote future is very low.

and Hosko 2007).

The Storm King Mountain PHS project in New York encountered vehement local opposition and a legal dispute that lasted 17 years (1963–1981). The defeat of this project was a landmark case[14] in the history of the modern environmental movement. Since then, hydro power projects (including PHS) have generally encountered local oppositions. The collapse of natural gas prices in the late 1980s and the restructuring of power market in the 1990s also unfavorably changed the economics of PHS projects. At least six proposed PHS projects[15] have been cancelled since the 1980s. Most of the cancelled projects had been through over 10 years of development.[16] Market uncertainty was the main stated cause of termination.[17]

Although assessments in the past have indicated a number of feasible sites for PHS, they were based on antiquated environmental criteria. However, technologies have progressed in the past two decades. The costs of tunneling and excavating have dropped significantly, and technologies for mitigating the environmental impacts of PHS have also improved.[18] Because PHS may be the least-cost energy storage, disregarding this option without an updated assessment would be imprudent.

A private consulting engineering firm, Devine Tarbell & Associates Inc.,[19] indicates an ongoing revival in PHS. Owners of existing pumped storage facilities are reevaluating their assets and, in many cases, rehabilitating and upgrading them. Some investors are also evaluating the feasibility of adding pumped storage facilities at existing reservoirs (Bishop 2008). Due to its large-scale nature, an upgrade of an existing PHS facility may add capacity equivalent to tens or hundreds of battery systems.

Of the existing 80,000+ dams in the United States, fewer than 3% are equipped with hydropower generators. Many existing dams could be retrofitted to produce electricity with limited environmental effects (National Renewable Energy Loboratory 2002). Some of these existing dams are suitable for PHS.

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[14] http://library.marist.edu/archives/mehp/scenicdecision.html. The opposition did not specifically target this project because it was an energy storage project; the Storm King case recognized the right to sue for non-economic interests, such as aesthetic or environmental interests. This case marked the beginnings of a new era of environmental advocacy in the U.S. that combined the use of legal tools with media outreach, public relations, and government lobbying.

[15] Dry Fork in Wyoming, Summit in Ohio, Blue Diamond in Nevada, Mt. Hope in New Jersey, River Mountain in Arkansas, and Crystal Creek in California.

[16] This is based on case studies of cancelled projects conducted by the author.

[17] This is also based on case studies.

[18] For example, the design of hydroelectric turbine improves in fish passage survival, ladders or other devices are installed to allow fish to migrate over dams, and screens can be installed to keep fish away from turbine blades. There are also improved practices that may reduce impacts on water quality.

[19] http://www.devinetarbell.com/hydropower/pumped_storage.htm.

An estimate suggests that an additional 78 GW of PHS capacity could be developed at existing reservoirs (Bishop 2008).

Interest in developing new PHS sites is growing. As of August 5, 2008, the FERC has issued 10 preliminary permits[20] for new PHS projects with total capacity of 5.8 GW. Whether these PHS projects will eventually be successful remains highly uncertain. Public attitude and policymakers' support will likely be the main determinants.

A typical hydropower (including PHS) license is valid for 30–50 years. Many hydro and pumped hydro facilities are undergoing re-licensing processes or are scheduled for re-licensing in the next decade. The re-licensing process can take 5 to 7 years, require extensive studies, involve contentious litigation, and cost tens of millions of dollars (Pospisil 1996). The reason most often given for cancellations of hydropower projects is the length and complexity of the licensing and re-licensing process (Mischkot 2006). Without policies to streamline the regulatory processes, the licensing difficulties could remain an obstacle in PHS development, even for those at existing reservoirs.

The ownership of hydroelectric generating capacity in the United States is distinct from other power generation technologies.[21] The federal government (Army Corps of Engineers, Bureau of Reclamation, and Tennessee Valley Authority) is the largest owner of hydroelectric capacity (44% of total). Non-federal public entities (irrigation districts, cities, and water districts) own 21%. Private non-utility companies own 11%. Private utility companies own 24%. The federal government may be the best-positioned agent for developing new PHS projects. Furthermore, a substantial portion of potential PHS sites are on federal land. PHS may present an opportunity if the U.S. federal government wishes to develop energy storage capacity directly.

B. Compressed-air energy storage (CAES)

Some studies suggest that compressed-air energy storage hold great potential in the United States (Succar and Williams 2008, Cavallo 2007). CAES is essentially a modified gas-fired power system. In a pure gas turbine power station, about two-thirds of the electricity output is used in compressing its combustion air. By utilizing pre-pressurized air, the thermal efficiency of a CAES gas turbine is usually about three times higher than that of a pure gas turbine. Because CAES systems burn natural gas to generate power, it is not free of carbon emissions. The emissions from a wind/CAES facility are estimated

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[20] A preliminary permit grants the developer priority right to a particular site. It is not a license.

[21] http://www.ferc.gov/industries/hydropower/gen-info/regulation/present-dev.asp.

to be 237 grams per kWh output[22] (Denholm and Holloway 2005). By comparison, natural gas-fired plants release about 430 grams per kWh (Thorpe 1998). Although CAES is not widely employed, it is generally believed to be commercially viable.

Currently there are only two operating CAES systems in the world. The first commercial CAES was a 290-MW unit built in Huntorf, Germany, in 1978. The second commercial CAES was a 110-MW unit built in McIntosh, Alabama, in 1991. The round-trip efficiency for the McIntosh facility is about 66%.[23] The construction of the McIntosh CAES facility took 30 months and cost $65M (about $591/kW).

Since the Huntorf facility began operation, other proposed facilities have undergone some level of development, including a 500-MW facility in Texas; a 1,050-MW facility in the former Soviet Union; a 300-MW facility in Israel; a 100-MW facility in Luxembourg; a 25-MW facility in Sesta, Italy; and a 35-MW facility in Japan (Baxter 2006). None of these projects has been completed, and reasons why development stopped have not been given publicly. In almost all discussions of CAES, the two successful experiences are cited as proofs of the commercial viability of CAES technology, while the unsuccessful ones simply ignored.[24] The promise of CAES may have been overestimated.

Both existing CAES plants stored air in caverns in salt domes, which are the best options for building CAES reservoirs. Unfortunately, salt domes are rare and their distribution match wind resources poorly. It is technically possible to construct CAES reservoirs at other geological formations, including salt beds and aquifers.[25] With this broadened definition, it has been estimated that over 80% of the United States contains one or more of these geologies and could be the location of a CAES plant (EPRI PEAC Corporation 2003). However, it would be optimistic to assume that every untested salt bed and aquifer is suitable for CAES. It requires a very detailed and often expensive geological study to identify a suitable location for CAES reservoir.

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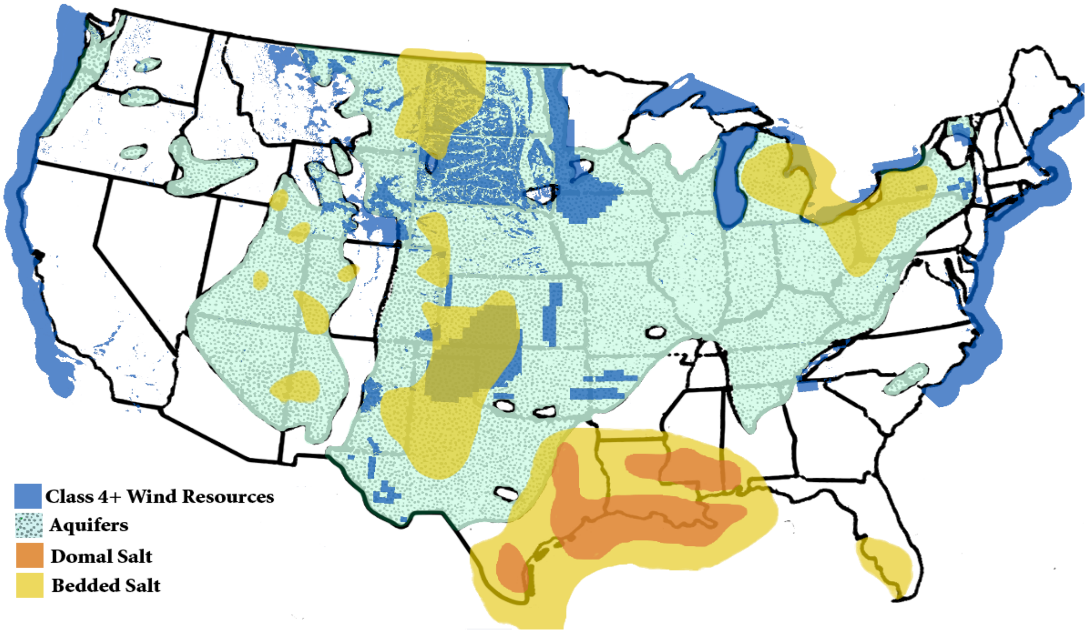
[22] Assuming no emissions from the (wind-generated) electricity used to compress air.

[23] Due to the hybrid nature of CAES, the efficiency estimates must be based on an assumption of the contribution of its gas input. Existing estimates adopt 35% thermal efficiency in evaluating gas' contribution to electricity output. The round-trip efficiency of the McIntosh facility was calculated with data provided by Mr. Lee Davis (e-mail on September 2, 2008), operator of the McIntosh CAES facility. (According to Mr. Davis, the McIntosh CAES system uses 0.8 kWh of electricity and 4,568 BTU of natural gas to generate 1 kWh of electricity.)

[24] This behavior is consistent with the *planning fallacy* phenomenon observed by social psychologists. The planning fallacy is a common psychological bias in which planners evaluate their current projects with best-case scenarios even though similar tasks in the past have typically failed.

[25] It is also possible to utilize rock cavern for CAES. However, the cost of creating a rock cavern is very high. This approach is only feasible if there is an existing rock cavern, such as the abandoned mine in the Norton project.

Figure 3: Areas with Geologies for CAES and Wind Resources (Succar and Williams 2008)



Norton Energy Storage (NES) filed application for construction of a CAES facility at an abandoned limestone mine in Norton, Ohio, in January 2001. Because this is the first attempt to build a CAES facility with a rock cavern, Sandia National Laboratories subsidized this “proof-of-concept” project (CAES Development Co. 2004). The site certificate was approved in May 2001 and the original startup date was set for the summer of 2003 (Global Power Report 2001). However, the NES failed to secure the required $1.5 billion in financing and suspended the project indefinitely in October 2002 (Global Power Report 2002). Since then, NES has successfully extended the site certificate twice.[26] The most recent extension allows the certificate to remain valid until May 21, 2011 (Global Power Report 2008). The NES continues to insist that they are still pursuing this project, but there is no definitive timetable. Financial difficulties appear to be the main cause of delays. The situations in the current financial market suggest that this project might not start construction any time soon. This example not only demonstrates the difficulties in financing a CAES project, it also demonstrates the insufficiency in the U.S. federal government’s energy storage R&D budget. The required financing ($1.5 billion) for this one project is over 700 times higher than the federal government’s entire budget ($2 million in 2008) on energy storage R&D. Unless the government dramatically expands its budget, it will not be capable of offering significant assistance to the development of large-scale energy storage.

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[26] The company first cited the Enron bankruptcy as the cause of financing difficulties in 2002. The original certificate was scheduled to expire in May 2006. It was extended to November 2008. In 2006, the company asserted that the conditions have rebounded. In 2008, it attributed the delays to the “2007–2008 constriction in the nation’s financial and credit markets” and obtained another extension.

The Iowa Stored Energy Park (ISEP) was first proposed in 2003 by a consortium of municipal utilities. It was originally scheduled for start-up during the summer of 2006 (Baxter 2006). The ISEP planning committee decided to store compressed air in an aquifer. They have been working to find a usable site in the past five years. The testing results of the first chosen site showed that the cap rock was inadequate for holding the compressed air. A second site was also proven unusable and abandoned. Testing and analysis are being conducted on the third site. Finding the right geological formation appears to be a difficult prospect. The most recent estimate is for the project to be online by May 2011. The utilities have spent $1.2 million on feasibility studies (Global Power Report 2008). The Sandia National Laboratories also contributed about $3.5 million (Global Power Report 2007). Although it is technically possible to use aquifers as CAES reservoirs, the testing adds time, cost, and risk. This example suggests that 30 months (based on the McIntosh experience) may be an optimistic schedule for CAES projects with aquifer geology.

An important advantage of CAES is that this technology can be built upon existing gas-fired infrastructure. CAES is essentially a gas-saving technology for gas-fired power plants. Gas-fired turbines are inexpensive, reliable, and can be constructed rather quickly. Because the storage reservoir is underground, the environmental impacts are limited or at least largely invisible to the public. So far the site licensing processes are relatively quick and easy. Nevertheless, there are serious technical and financial risks in CAES projects. The preliminary assessment of underground conditions and the excavation can be very time-consuming and expensive. The large upfront capital investment must be justified by long-term savings in natural gas expenditures. With a volatile natural gas market in which prices have fluctuated in the last 10 year by an order of magnitude, further financial support may be needed for the deployment of CAES.

C. Rechargeable batteries

Several types of rechargeable batteries are being tested and installed as pilot projects by the utility industry. The most promising battery types include sodium-sulfur (NaS) batteries and flow batteries. The advantages of battery storage include high efficiency, relatively compact size, and flexible location. The round-trip efficiencies range from 70% to over 90%. The main constraint is their high cost. Another disadvantage of batteries is that they often suffer from memory effect.[27] Their lives are in the range of 10 to 15 years—significantly shorter than those of PHS and CAES. For momentary (seconds or minutes) outage mitigation, some batteries are already commercially competitive. However, for large-scale

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[27] Memory effect is an effect observed in rechargeable batteries that causes them to gradually lose capacity over time.

storage (hours), batteries usually cost more than an order of magnitude more than PHS on the basis of per recharge cycle and many times higher than CAES. In Japan, where the electricity rate is significantly higher than the United States, a sodium-sulfur battery is considered competitive for PS functions. There is about 165 MW of installed capacity of NaS batteries (in demonstration projects) in Japan.[28]

American Electric Power installed the first U.S. demonstration of a NaS battery in 2002 in Gahanna, Ohio. This project was partially funded by Sandia National Laboratories. The system is equipped with two modules of 50-kW NaS batteries capable of storing up to 7.2 hours of electricity. The life of a NaS battery is estimated to be around 15 years, or 2,500 cycles. The estimated cost of a 250-kW NaS system (five modules) is $605,000. The per-kW capital cost is $2,420 (2006 pricing) (Norris, Newmiller and Peek 2007).

Japan Wind Development Company has installed a NaS battery at its Futamata wind farm. The company reported that the experimental battery-supported wind farm is already yielding profit, because the battery enables them to sell all electricity at peak-load prices which are five to seven times higher than the average level at which they have been selling (Yamanaka and Firn 2008). Xcel Energy also recently installed NaS batteries at Luverne, Minnesota, to store energy from the nearby Minwind Energy wind farm (Buntjer 2008).

Sodium and sulfur are both abundant resources. The high costs mainly come from the manufacturing processes rather than materials. Currently the NaS battery market is monopolized by the Japanese company NGK Insulators. If demand continues to grow, new producers may enter this market and the production may scale up to the point at which prices decline. Further research into alternative materials for the ceramic electrolyte may present opportunities to further improve the performance of NaS batteries (Walawalkar and Apt 2008, Wen, et al. 2008).

A flow battery is another form of rechargeable battery that may be a candidate for PS grid energy storage. A flow battery stores electricity in chemical components that are dissolved in liquid electrolytes. Flow batteries are typically named after the electrolyte they use. The main types include vanadium redox, polysulfide bromine, zinc bromine, and cerium zinc (Baxter 2006). Vanadium redox appears to be the most mature type among flow batteries. Compared with NaS batteries, flow batteries can be more easily scaled up by adding more electrolytes. However, the commercialization of flow batteries appears to lag behind NaS batteries.[29] The installed capacity of flow batteries worldwide is only in the range of tens of

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[28] Most of the installed NaS batteries are for PQ purpose. A few of them also operate at PS mode.

[29] Two reasons may explain the lag. First, currently the costs of flow batteries are significantly higher than NaS

MW.

Lead-acid and nickel-cadmium batteries have historically been used for grid applications. However, these batteries use toxic materials and may be gradually phased out. Lithium batteries are widely used in mobile electronic devices and are increasingly considered for hybrid and plug-in hybrid vehicles. Currently, lithium batteries cost too much for grid applications. If costs decline significantly (over 90%) in the future, they may find applications on the grid.

Further research and development in batteries would be useful for utilities in mitigating momentary outage and improving PQ. For PS purpose, the major barrier is cost. For batteries to serve PS grid electricity storage, the costs must be further reduced.

D. Flywheels

Flywheel is commercially available both as consumer uninterruptible power supply (UPS) products and as PQ-purpose grid energy storage. UPS is niche market within the PQ category. Currently, flywheels are not used for PS purposes. For commercial PQ-function flywheels, their round-trip efficiencies are around 70–80%. All commercially available flywheels are designed with less-than-a-minute discharge times. However, it may be possible to design and produce long-duration flywheels. One company[30] claims to have developed a flywheel with 3 hours of discharge time.

The major challenge in producing long-duration flywheels is to reduce standby power losses. Further R&D efforts are required to develop long-duration flywheels. Superconducting magnetic bearings can operate without friction, but existing superconducting materials require cryogenic cooling, which consumes power. The development of high-temperature superconducting materials may present opportunities for flywheels to operate without friction and less cooling (EPRI PEAC Corporation 2003). Developments of new materials may also improve performance and reduce costs (Ruddell 2003).

E. Hydrogen

Hydrogen energy storage for wind power has been installed in one demonstrations project and another is under construction. These projects alone, however, do not indicate commercial viability as they are

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batteries. Second, exactly because it is very easy to expand the capacity of a flow battery, there is little incentive to build prototype projects with large capacities. On the other hand, the correlation between small and large NaS batteries is not as direct as in flow batteries. Therefore, there is a higher incentive to build NaS prototype at full commercial scale.

[30] Beacon Power.

entirely funded by governments.

The world's first (and currently only) full-scale stand-alone wind-hydrogen power generation unit has been installed in Utsira, Norway. The Utsira system is a fully government-funded demonstration project. The Utsira system is equipped with multiple backup technologies. Its hydrogen system has both an internal combustion engine (ICE) and fuel cells, and it is also equipped with a battery and flywheel (Hagen 2004-2005). Its design makes the system highly reliable but inevitably very expensive. Comparing cost and efficiency of such a complex system with other technologies is difficult.

Another pilot project of integrated wind power and hydrogen energy storage system is under construction at Ramea Island, Newfoundland, Canada.[31] This project developer uses a hydrogen internal combustion engine in the system and expects a round-trip efficiency of 25% (Oprisan 2007). If the internal combustion engine were replaced with fuel cells, the round-trip efficiency could increase to about 35%. However, fuel cells face an additional challenge: short life (< 5,000 hours) and high cost (Chalk and Miller 2006).

The National Renewable Energy Laboratory conducted a study on wind-battery-hydrogen integration (Fingersh 2004). The study concluded that "with the electrolyzer and fuel cell efficiencies set to 75% and 50% (probably optimistic values), the closed cycle efficiency of the hydrogen system is only 37.5%." According to its modeling results, even if the capital costs of the electrolyzer and fuel cell were both set to zero, a hydrogen energy storage system cannot compete with a battery due to the large gap in efficiency. This efficiency gap may be insurmountable without revolutionary breakthroughs for hydrogen storage systems. Innovative approaches such as reversible fuel cells and high-pressure electrolyzers may present possibilities for such breakthroughs (Schainker 2004).

Due to the low efficiency in converting hydrogen back to electricity, many proposals of wind-hydrogen integration favor using hydrogen as vehicle fuel instead of converting it back to grid electricity (Linnemann and Steinberger-Wilckens 2007, Sherif, Barbir and Veziroglu 2005). This strategy will only be feasible if hydrogen vehicles are widely adopted.

F. Smart-grid-enabled diverse energy storage

An ice-storage air conditioner is a good example of technologies that sit on the boundary of energy storage and load-shifting. Ice-storage air conditioners use cheap off-peak electricity to produce ice. The

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[31] The project is funded entirely by the Canadian federal government and Newfoundland provincial government. It is therefore not considered a commercial application.

stored ice is used to provide cooling when the service is needed. The dynamic utilization of demand response resources may also respond to intermittent energy output. Irrigation is an example of demand response resources. Pumping water for irrigation is highly flexible in its time of operation. With a smart grid, it may be possible to automatically start pumping water when the wind blows. In order to take advantage of diverse energy storage and demand response resources, the deployment of smart grids is a prerequisite.

In addition to smart grids, it requires appropriate pricing structure to justify investments in diverse energy storage. The key elements are net metering and time-of-use pricing. Net metering makes it possible for electricity customers to sell power back to the grid. Time-of-use pricing set higher prices for peak hours so there would be a financial incentive to shift loads. The Energy Policy Act of 2005 (by amending Section 111(d) of the Public Utility Regulatory Policies Act of 1978) requires each state regulatory authority and utility to consider and determine whether or not to offer time-of-use pricing and make net metering available to their customers. With both time-of-use pricing and net metering, small energy storage investors may be able to generate revenues from power arbitrage. Retail customers are unlikely to invest in energy storage purely for power arbitrage. However, many electricity customers are already investing in energy storage devices to improve their PQ.[32] With net metering and time-of-use pricing, the additional profits from power arbitrage may create a niche market (PQ/PS dual purposes) in diverse grid energy storage.

Many automobile companies are planning to sell plug-in hybrid vehicles. With a smart grid, it would be possible to store intermittent renewable energy in a potentially huge array of vehicular batteries. Plug-in hybrids will mostly be charged in the evening and nighttime hours when people are at home. Vehicular batteries (likely lithium batteries) are much more expensive than the grid-tied energy storage options discussed above, however. If vehicular batteries are programmed to be available for grid operation, the increased charge/discharge frequency would shorten the lives of vehicular batteries. It would require further assessments to determine whether it would be economical to utilize vehicular batteries for grid operation.

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[32] For example, a lead-acid battery recycling plant in Vernon, California, has installed a lead-acid battery system to provide both peak demand reduction and uninterruptable power (Baxter 2006). Numerous small battery UPS systems are installed in hospitals to provide continuous power to the devices supporting the patient, avoiding loss of critical information, and aiding in the smooth functioning of facilities and emergency (Munafó 2008).

the Climate Change Policy Partnership

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