and these technologies could potentially address the residual demand that is very difficult or expensive to meet with RE resources and storage deployed in Phases 1–3.

Our four phases framework is intended to describe a plausible evolution of cost-competitive storage technologies, but more importantly, it identifies key elements needed for stakeholders to evaluate alternative pathways for both storage and other sources of system flexibility. Specifically, an improved characterization of various grid services needed, including capacity and duration, could help provide a deeper understanding of the tradeoffs between various technologies, and non-storage resources such as responsive demand. Such a characterization would help ensure the mix of flexibility technologies deployed is robust to an evolving a grid, which will ultimately determine the amount of storage and flexibility the power system will need.

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1 Introduction

For the first century of the electric power system in the United States, electrical energy storage provided a small fraction (less than 3%) of the total system capacity (1). But with declining costs and the promise of new storage technologies and increased deployment of variable renewable energy (VRE) resources, interest in the potential for large-scale deployment of energy storage is growing.

In a competitive and highly regulated industry, storage must provide cost-effective services that meet system needs. In this report, we describe a value proposition for energy storage that could result in cost-effective deployments, which could reach hundreds of gigawatts (GW) of installed capacity and result in a significant change in the nation's electric grid. Section 2 and 3 of this report set the stage for recent and future energy storage deployment in terms of valuation, costs and benefits. Sections 4–7 then describe a vision of future storage deployment following four phases:

- **Phase 1:** Short-Duration Storage for Providing Operating Reserves (Section 4)
- **Phase 2:** The Rise of Battery Peaking Power Plants (Section 5)
- **Phase 3:** The Age of Low-Cost Diurnal Storage (Section 6)
- **Phase 4:** The End Game: Multiday to Seasonal Storage (Section 7)

While we present four distinct phases, the boundaries between each phase will be somewhat indistinct, as described in subsequent sections. Each phase is described in terms of storage duration and the corresponding services provided. We discuss technical and market requirements, including an estimate of the potential deployment in each phase and how transition points might occur as market opportunities for shorter-duration storage become saturated and storage duration costs decline.[2] We also demonstrate how the size of each phase (particularly Phases 2–4) are heavily influenced by VRE deployments that impact net load shapes.

The first of our four phases—the deployment of short-duration (under 1 hour) storage capacity for providing operating reserves—has actually been underway for nearly 10 years. The second phase, which has more recently begun in some locations is the deployment of battery peaking plants with 2–6 hours of duration. The third phase represents a transition to lower cost and potentially longer-duration storage that could include a range of technologies in various stages of commercial development. The final phase is very long duration (greater than 12 hours to seasonal) storage that potentially becomes economic under scenarios of extremely large-scale renewable energy (RE) deployment, including under scenarios of 100% RE grids or scenarios of certain technology breakthroughs.

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[2] This concept of phases in the evolution of the power system is similar to that proposed by the International Energy Agency for renewables deployment (2). They describe six phases that are aligned with increased levels of variable RE deployment, and each phase requires a different set of measures to address the resulting variability and uncertainty of net load. This is somewhat similar to how our phases vary as increased storage (and RE) deployment create changes in net load and grid services needed.

Our intention for this work is to consider the potential for large increases in energy storage deployment in the United States so that utilities, regulators, and developers can be better prepared for this deployment and can understand the need for careful analysis to ensure cost-optimal deployment. This work also considers the changing role of storage as the grid evolves and the importance of storage as a capacity resource increases.

While we identify large potential opportunities for storage technologies based on currently monetizable services, actual deployment opportunities are highly uncertain, particularly for later phases (primarily Phase 3 and Phase 4), which may require new technologies with uncertain cost and performance trajectories.

2 Historical (Pre-2010) Deployment of Energy Storage

Before the introduction of restructured electricity markets, which began largely in the early 2000s, the United States had about 23 GW of electrical energy storage deployed, virtually all of it in the form of pumped storage hydropower (PSH) (1). This storage was built largely as an alternative to conventional fossil-fueled peaking capacity under the regime of least-cost planning by vertically integrated utilities (3). Many of these storage plants were planned and built in response to the prospect of very low cost baseload power being provided primarily by nuclear and coal plants but also in response to increasingly expensive sources of traditional peaking capacity such as steam plants burning high-cost oil and natural gas. Other motivations included restriction on the construction of gas-fired plants resulting from the Power Plant and Industrial Fuel Use Act of 1978. Pumped storage provided a means to increase the flexibility of baseload resources, enabling charging with off-peak energy and discharging during periods of higher demand, thus offsetting the need for (then) higher-cost oil- and gas-fired capacity.

Between 1960 and 1985, about 20 GW of the 23 GW of electrical energy storage capacity was built, often with long lead times that resulted in some limited deployment into the 1990s. Figure 1 shows the cumulative historical deployment of these pumped storage plants up to 2010, and also all other storage technologies (largely a single compressed-air energy storage facility completed in 1992).

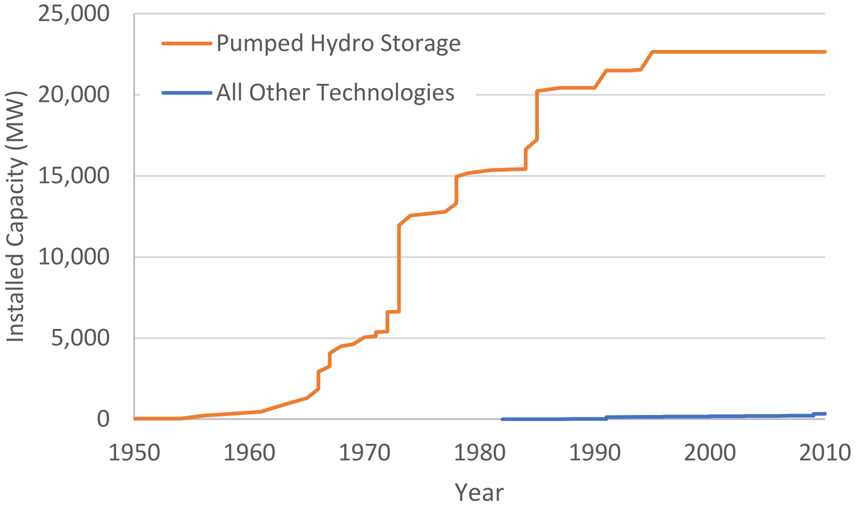


Figure 1. Cumulative electricity storage deployment, 1950–2010

The multidecade-long hiatus in significant storage deployment after the early 1990s can be attributed to a variety of factors, including the advent of more cost-effective gas turbines, repeal of the Power Plant and Industrial Fuel Use Act of 1978, and lower-cost natural gas. These factors resulted in the development of natural gas-fired power plants to provide peaking capacity and very limited storage deployment (of any type) between 1990 and 2010.

The existing PSH plants continue to provide firm capacity, energy time-shifting, and multiple operating reserves, and they are expected to continue providing these services for the foreseeable future, with their role adapting as the grid evolves, such as increasing use for integration of RE or grid black start capability (4, 5). Therefore, deployment of new storage in our four phases framework supplements the services already provided by existing pumped storage. In addition, upgrades to existing pumped storage plants are also possible, and they would improve efficiency and response time (6). Deployment of new, next-generation pumped storage is discussed in Section 6 (associated with Phase 3.)

3 Setting the Stage for Recent and Future Deployment: Valuation, Costs and Benefits

New storage will be deployed based on its ability to potentially provide a cost-effective alternative or supplement to the various technologies that currently provide the host of services needed to maintain a reliable grid. Our four phases framework connects grid services with durations required to provide those services. The four phases reflect the evolving value proposition and cost structures for energy storage, starting with high-value, short-duration services, followed by storage progressively providing services that require longer durations, and in some cases, have lower value and thus require lower costs.

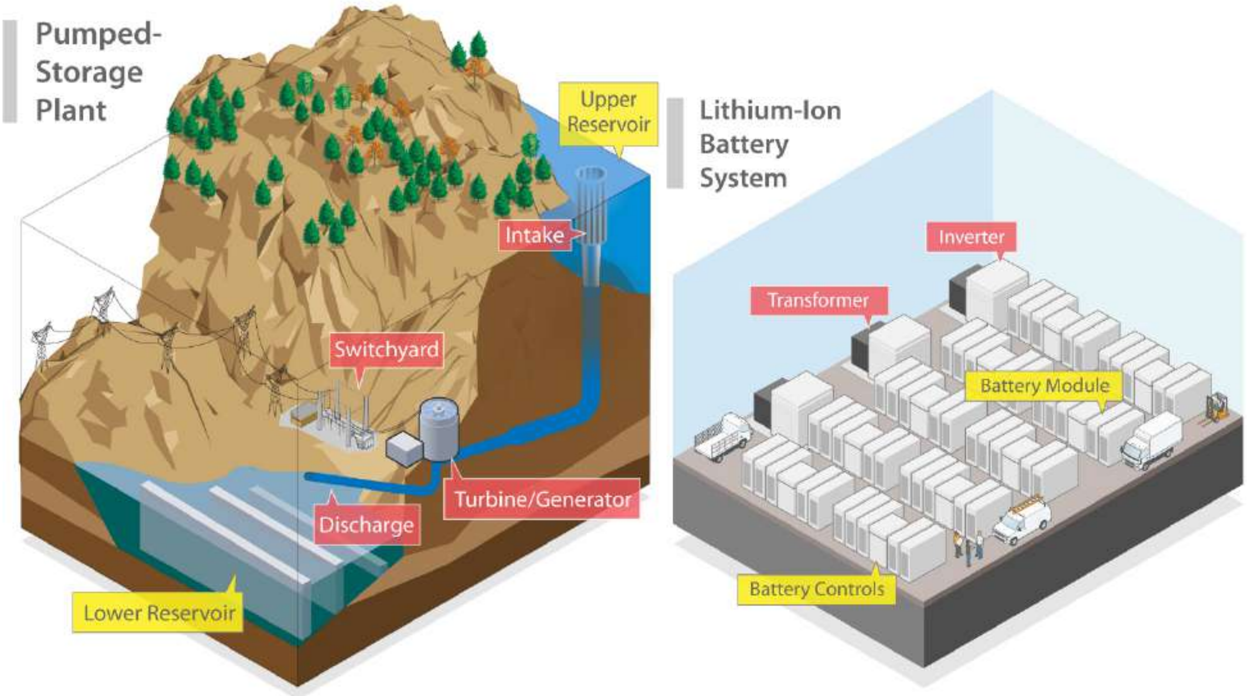
Assessing the economic performance of a new storage plant—whether it is a developer determining the plant's stand-alone economic performance or a vertically integrated utility comparing it to alternative resources—involves estimating the cost and benefits (or revenues) over the life of the project and comparing the associated economic performance with those of alternative resources or investment options. Example costs and benefits are discussed below to demonstrate the implications of the four phases framework.

3.1 Storage Costs

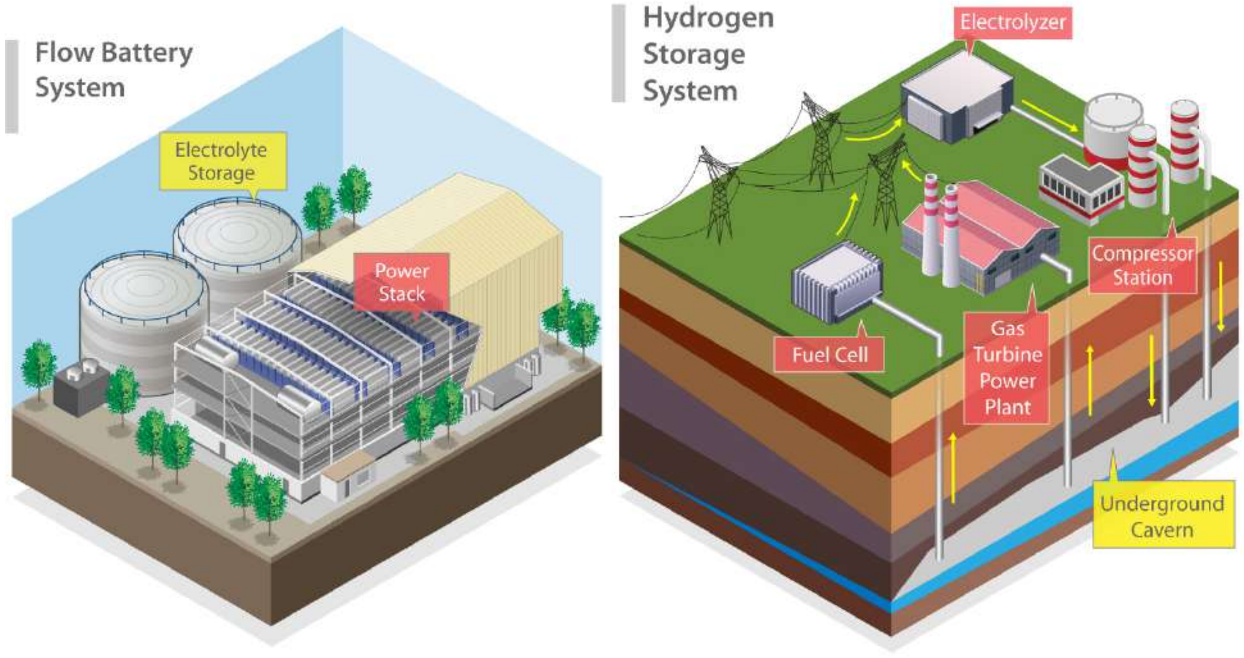
The cost of traditional power plants typically includes initial fixed capital costs, ongoing fixed costs, and a variety of variable costs, including fuel and operation and maintenance.

A major difference between the capital costs of storage and conventional plants is that storage—unlike a conventional technology—has two components: power and energy. Because electricity is almost always stored in another form (e.g., potential energy of water, electrochemical bonds, or kinetic energy), power conversion equipment is required to convert electricity into this other form and then back again using pumps, power electronics, or other technologies. This process represents the power component of a storage plant and associated costs.

The energy component of storage is associated with the storage medium (e.g., water, chemicals, or rotating mass) and the container that holds the medium. Figure 2 illustrates these components (in a simplified manner) for several different storage technologies, with power-related components shown in red and energy components shown in yellow. For some technologies, such as hydrogen and flow batteries, there is a fairly clear distinction, with the power component being largely a stand-alone set of equipment, while the energy component consists of a storage tank or underground formation for the storage medium (hydrogen or electrolyte). For other batteries, such as Li-ion batteries, the design and construction of the battery module influences its power capacity, which somewhat reduces the absolute distinction between power and energy.



(a) Pumped storage hydro (b) Li-ion battery

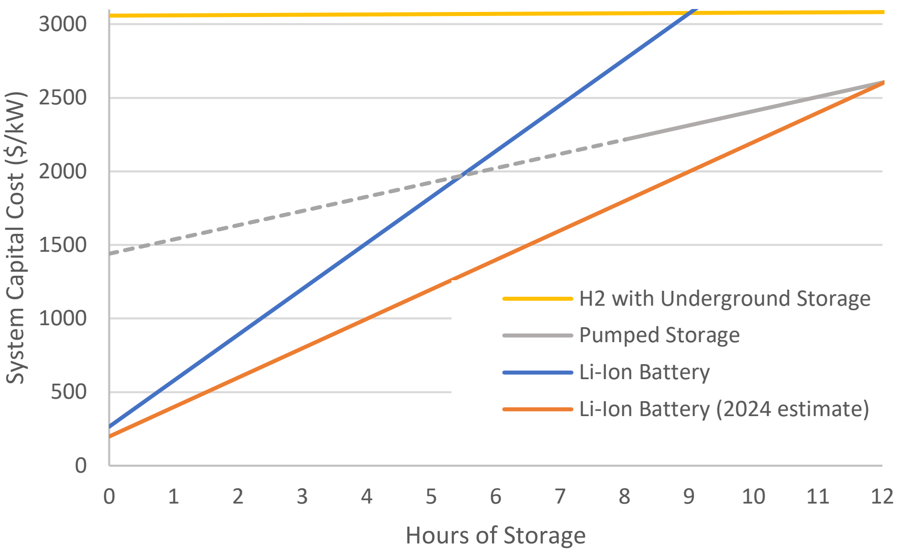


(c) Flow battery (d) Hydrogen

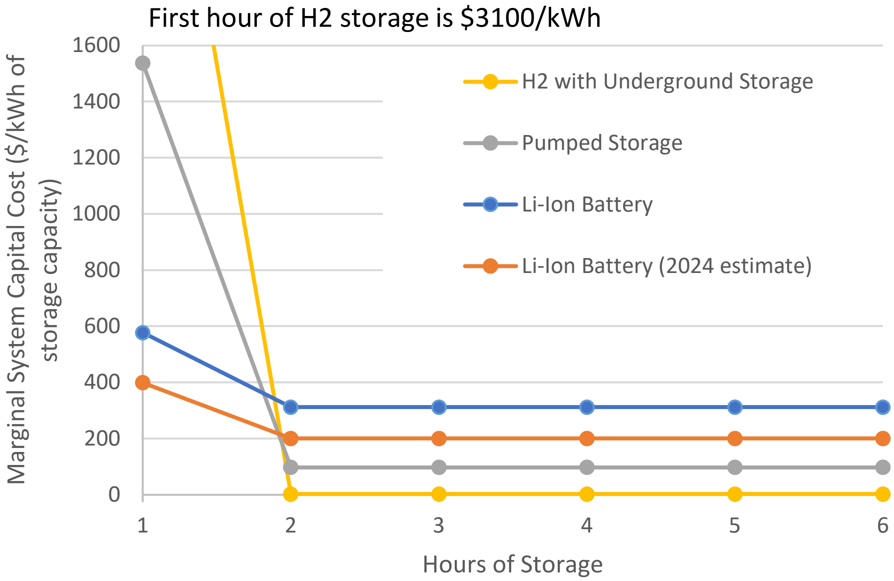
Figure 2. Power versus energy components in an energy storage power plant

Power-related components are annotated in red and energy components in yellow. Images are not to scale

Because storage plants have both a power component and an energy component, the cost of a storage power plant increases continuously as a function of duration for most technologies. Figure 3 illustrates the relationship between duration and cost for three types energy storage technologies using cost estimates from (7).



(a) Total capital cost



(b) Incremental capital cost

Figure 3. Simplified relationship between capital cost of energy storage and duration using 2020 cost estimates (7)

kW = kilowatt, kWh = kilowatt-hour, H2 = hydrogen