Energy Storage Futures, Volume 1: Types and Services

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1. Introduction

The National Renewable Energy Laboratory (NREL) over the last year released a six-section study titled "Storage Futures Study," hereafter SFS. The high-level goal of this was to model energy storage systems' implementation out to 2050. However it also takes a deep dive into how these systems are currently used, will be used in the future, the economics and technology surrounding their use along the way. This study's home page is referenced here.[1]

There are currently six sections in this series, and a seventh is planned sometime later in 2022. As I start to write this series my current intent is to track each of these sections with a much shorter summary of each SFS section (section 1 of SFS is 50 pages long and this summary is 12 pages long). Since I recently stopped posting a second paper every week on Thursday, I will complete each Energy Storage Futures paper, go through my normal proofing process, and then post each on a following Thursday.

2. Types of Energy Storage Systems

The first section of SFS is referenced here.[2] The authors identify four types of energy storage systems primarily based on duration, but also on other criteria (energy capacity, time of evolution, etc.). At least in this section, they do not attempt to pick technology winners (smart), although they do use examples of technologies. As someone that monitors energy storage system technologies I know that there are many promising emerging technologies. By 2050, I expect the technology landscape will be one we cannot envision currently.

The energy storage systems types (phases) identified by this section are:

Phase	***Primary Services***	***National Deployment in Each Phase***	***Duration***	***Response Speed***
Deployment prior to 2010	*Peaking capacity, energy time-shifting and operating reserves*	*23 GW of Pumped Storage Hydro (PDH)*	*Mostly 8–12 hr*	*Varies*
1	*Operating reserves*	*<30 GW*	*<1 hr*	*Milliseconds to seconds*
2	*Peaking capacity*	*30–100 GW, strongly linked to PV deployment*	*2–6 hr*	*Minutes*
3	*Diurnal capacity and energy time shifting*	*100+ GW.*	*4–12 hr*	*Minutes*
4	*Multiday to seasonal capacity and energy time-shifting*	*Zero to more than 250 GW*	*>12 hr*	*Minutes*

[1] NREL, "Storage Futures Study", Jan 2021 (Section 1) through Jan 2022 (Section 6), note that there will be a seventh section sometime later in 2022, https://www.nrel.gov/analysis/storage-futures.html

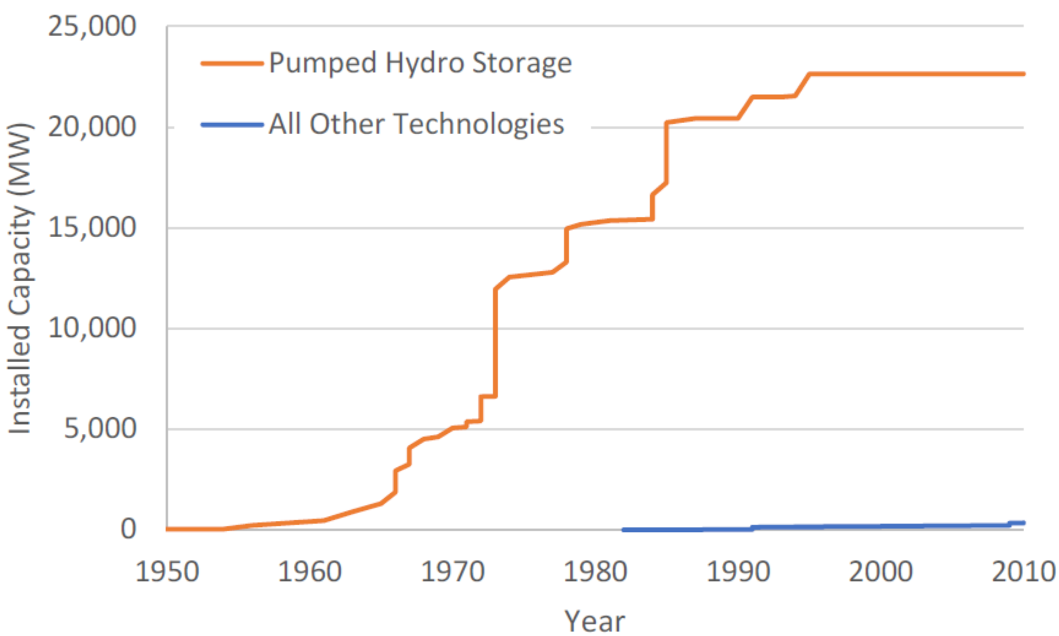
[2] Paul Denholm, Wesley Cole, A. Will Frazier, Kara Podkaminer, and Nate Blair, NREL, SFS, Section 1, "The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System," https://www.nrel.gov/docs/fy21osti/77480.pdf

Note that members (projects) in phases could easily move to adjacent phases depending on the value and demand of services and the cost of implementing them.

3. Applications

Most of the applications (Services in the above table) have been around for decades, and are standard grid-services. Prior to Y2K, these each had products addressing them. Also, the markets for these products were pretty stagnant prior to the year 2000.

The pumped hydro storage (PHS) market started emerging in the 1960s & 70s (see chart below). But largely stalled after Y2K.



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.

For a description of the Power Plant and Industrial Fuel Use Act of 1978, see the reference here.[3]

The existing PHS 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 renewable energy (RE) or grid black start capability. Therefore, deployment of new storage in our four phase framework supplements the services

[3] US Department of Energy, Office of Electricity, "Power Plant and Industrial Fuel Use Act," https://www.energy.gov/oe/services/electricity-policy-coordination-and-implementation/other-regulatory-efforts/power-plant

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...

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 phase 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 phase framework.

3.1. Energy Storage Systems 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 & maintenance.

A major difference between the capital costs of storage and conventional plants is that storage—unlike a conventional technology—has two components: power (MW) and energy (MWh). 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…

Note that each of the above components has a cost, Thus at its simplest, quantifying the cost of a particular energy storage system for a particular application requires determining the cost of each component ($/MW and $/MWh) for each use cycle over a period of addressing that application. Each of these two components has sub-components (or constituents, or parts). The most significant are described below.

$/MW (cost of power): cost-of-money for building the energy storage systems or debt-service; ongoing cost of maintenance.

$/MWh (cost of energy): cost of storing the energy, cost of releasing the energy, any impact on maintenance for a particular energy storage/release profile.

3.2. Basic Applications

The Table below defines **basic** types of applications.

Four Major Categories of Bulk Power System Storage Services Service	***Description***
Capacity	*Firm capacity*
Energy	*Energy shifting/dispatch efficiency/avoided curtailment*
Transmission	*Avoided capacity, congestion relief*
Ancillary services	*Operating reserves, voltage support*

Note that the above table does not explicitly list RE-specific applications, such as “renewable firming” or “renewable time-shifting.” These applications are specific cases of the more general applications listed and are therefore already captured this table.

Likewise, the above table captures some applications that can be provided by behind-the-meter storage. For example, firm capacity and energy shifting value is reflected in tariffs by demand charges and time-of-use rates. However, the table does not include several additional values provided by distribution- or customer-sited storage, including avoided upgrades and local reliability and resiliency. We focus here exclusively on utility-scale storage; other analyses within the Storage Futures Study examine the potential value, costs, and potential adoption of behind-the-meter storage…

Section 1 of SFS spends quite a bit of time on economic considerations, and I’m not going there.

Also, this section has a short subsection pointing out that a particular application can frequently be provided through multiple technologies. I would only add, that although this is generally true, considering competiveness means that a particular technology (1) leads the market for a particular service at a particular time, and (2) technologies that have the potential to rapidly lower their costs in the future will probably increase their market-share in the future (all other factors being equal).

Section 1 of SFS drills-down on each similar set of services and the type of energy storage systems that will probably address them. The sections below track these. The “Phases” in the titles comes from the table on page 1 of this paper.

4. Phase 1, Short-Duration Energy Storage Providing Operating Reserves

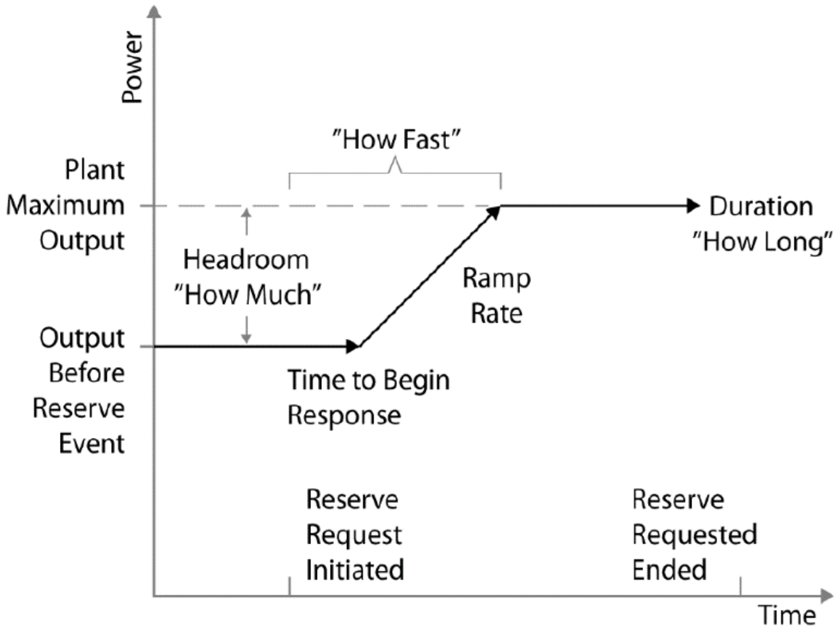
After the minimal deployment of storage that occurred after the 1980s, interest in storage was renewed in the early 2000s with the convergence of several events. One was the creation of wholesale markets. These markets eventually included several operating reserve products that provided storage an opportunity to directly compete and demonstrate its potential value compared to resources that have traditionally provided these services.

While operating reserves consist of numerous services and market products, they all represent the ability of a generator or aggregated set of generators to increase output (provide “upward” reserves) or decrease output (provide “downward” reserves). These reserves are provided in response to random variations in supply and demand at various time scales. The distinctions between different reserve services can be characterized by three factors:

- *“How much” reflects the quantity of power potentially needed by the system, or how much headroom is needed from the set of plants providing this service; this is measured in power capacity (megawatts [MW]).*
- *“How fast” reflects the response rate needed or how quickly the set of plants providing the services are required to move from one setpoint to another (MW/second) and is a combination of the time needed to initiate a response to the reserve event and ramp rate.*

- *How long is the duration for which the plants must hold the new output, and for an energy storage device, represents the amount of stored energy (megawatt-hours [MWh])*

The application of these three factors to a single plant is illustrated in the figure below, which shows the output of a generator that is operating below maximum output and able to provide some reserve capacity based on its operating limits.



Though specific operating reserve products have different names depending on the region, we focus here on two major classes that exist in all market regions in the United States and which offer higher value:

- *Spinning contingency reserves are used to respond rapidly to address the failure of large power plants or transmission lines.*
- *Regulating reserves are used to address smaller, random variations in supply or demand.*

We do not consider non-spinning or supplemental reserves, which are slower to respond and require a long-duration response of multiple hours.

In brief, "how much" each reserve produces is determined by each balancing area. How much of this can be provided by any individual storage asset is determined by its power capacity and operating state, meaning it must operate at less than full output (holding headroom) and hold sufficient energy to respond to a reserve call or event.

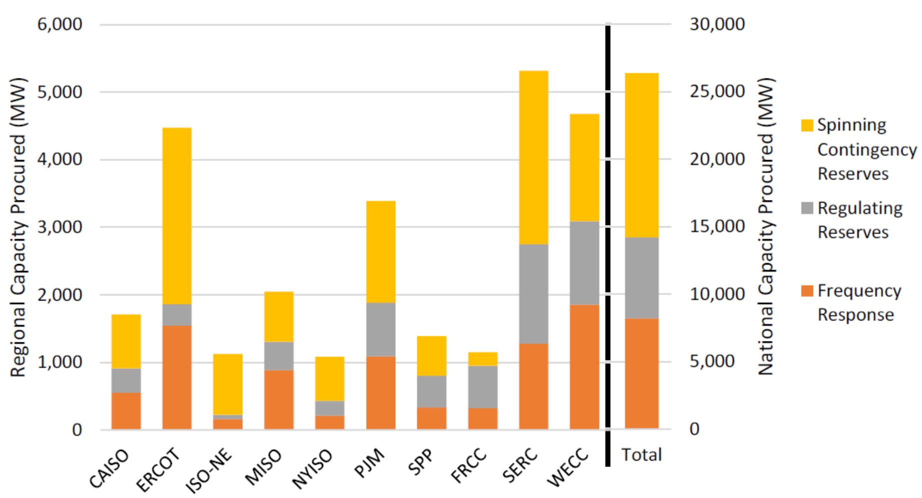
Each balancing area also establishes rules for the response rate ("how fast") required for generators to participate in the provision of operating reserves. For example, an operator might require a generator to increase output in 10 minutes for the provision of spinning contingency reserves.

Rules also establish the length of time a unit must be held at the increased output, typically in the range of 15–30 minutes. As an example, spinning contingency markets may require a resource providing this service to hold output for at least 30 minutes *(reflecting the time needed to bring up additional generation capacity). For a 1-MW storage device to be able to provide this service, it would need to have 30 minutes of discharge capacity or 0.5 MWh of stored energy…*

Historical market values can be used to estimate an approximate value for energy storage providing various services. Prices for operating reserves are often measured in units of capacity available during 1 hour (MW-hr). This is not a unit of energy—it represents capacity that is available for a response over a period of time. A facility providing spinning contingency reserves is paid for this provision even if there are no calls for providing energy; more simply stated, the plant is paid for doing nothing other than being ready to respond and then responding if called to do so. The average spinning contingency reserves market prices in 2019 ranged from $3/MW-hr to $27/MW-hr, with a national weighted average of about $11/MW-hr. A storage plant providing contingency reserves would essentially "idle" in a charged state, waiting for a response, and then be paid for the whole time. When called, the plant would then discharge until the end of the event and then recharge as soon as possible so that it could return to a charged state and provide reserves again.

Regulating reserves are more complicated. Unlike contingency reserves, which are rarely used, provision of regulating reserves requires a unit to change output fairly frequently in response to small, random variations in demand. A storage plant providing regulating reserves would sit at a condition with a high state of charge, but it would continuously increase and decrease output in response to grid needs… However, prices for regulating reserves are typically higher than those for contingency reserves; average 2019 regulating reserve prices in market regions ranged from about $6/MW-hr to $32/MW-hr for combined up and down reserves, and the weighted national average was about $15/MW-hr. This capacity-related payment is often supplemented by a payment associated with increasing or decreasing output…

Phase 1 is limited by the total amount of high-value operating reserves needed in the U.S. power system, as summarized in the figure below. Regulating reserves requirements are driven by the size of normal variability in net load, and contingency reserves are driven by the size of the largest expected power plant or transmission line failure in each region.



Note that the above figure is the current U.S. grid requirements for high-value operating reserve products potentially served by energy storage in Phase 1. Also note that this assumes a discharge time of only one hour at the bid output.

Two additional factors could extend Phase 1. The first is additional market products, including a flexibility/ramping reserve product that has been created to address additional variability and uncertainty in the minutes-and-beyond time scales resulting from variable renewable energy (VRE) deployment. This product has been introduced in a limited number of regions, and it typically requires a slower response rate (i.e., lower ramp rate) and longer duration (i.e., the resource holding output for longer) than regulating reserves.

The second factor that could extend Phase 1 is potential growth in regulating reserves that may result from increased deployment of VRE resources. However, several studies have found that much of the increase in variability occurs in time scales in the minutes-or-longer time scales, and it may drive the creation and use of a flexible ramping reserve, as opposed to very large increases in regulating reserves. So overall, there is no clear evidence for a very large growth in operating reserve requirements as a result of large VRE deployments. Overall, though it is limited, Phase 1 represents an important entry point for storage, particularly in regions with little prior storage deployment and for services where storage can offer higher value.

5. Phase 2: Energy Storage System Peaking Power Plants

As Phase 1 operating reserve markets saturate and declining battery prices create new opportunities, we transition to Phase 2: the deployment of batteries with about 2–6 hours of duration for providing peaking capacity. Peaking capacity is used to meet short periods of peak demand on hot summer days, or in some locations, in periods of extreme cold. Peaking capacity is typically provided by simple-cycle gas turbines, older gas steam plants, or internal-combustion generators. However, the continued decline in the costs of Li-ion batteries has increased their competitiveness over traditional sources, and Phase 2 has already begun in some locations.

Author's comment: The Storage Futures Study (SFS) is for the whole country, not just my state, but I need to point a unique characteristic about my state (California) when it comes to peaking power plants. Our summer peaks usually can be addressed by energy storage systems with a 4-hour duration. I will send you to section 2 of a reference with a link here[4] for a thorough explanation. This means that our natural gas-fired combustion turbine peakers are already being rapidly displaced by energy storage systems.

In Phase 1, we consider short-duration storage providing only a single service because of the power constraints of the battery…

Alternatively, a battery peaking plant typically provides multiple services, including provision of physical capacity (capacity credit), the value of energy time-shifting, and operating reserves during certain periods. A battery peaking plant can provide both capacity and energy shifting services simultaneously because the periods of highest prices (when the battery will discharge to maximize revenue or minimize system costs) are very highly correlated to periods of highest demand when the system needs reliable

[4] "Long Term Storage," June 2020, https://energycentral.com/c/cp/long-term-storage

capacity. Periods of low prices (when the battery will charge) are also periods of low demand, and therefore when large amounts of spare capacity are available and the risk of an outage is low. Therefore, these two services—capacity and time-shifting—do not double count either the energy or power capacity of the battery and can be "stacked."

5.1. Cost-Competitiveness of Energy Storage Systems Peaking Plants

If operating reserves are ignored, a battery peaking plant will obtain two sources of value (or revenue): capacity value and energy value.

Capacity value is the monetary value associated with providing physical capacity. The ability of this capacity to be available when needed is a critical component of this value. This is reflected in a generator's capacity credit, which is defined as the fraction of the generator's installed capacity that could reliably be used to meet peak demand (or offset conventional capacity), which is typically measured as a value (e.g., kilowatts) or a percentage of nameplate rating…

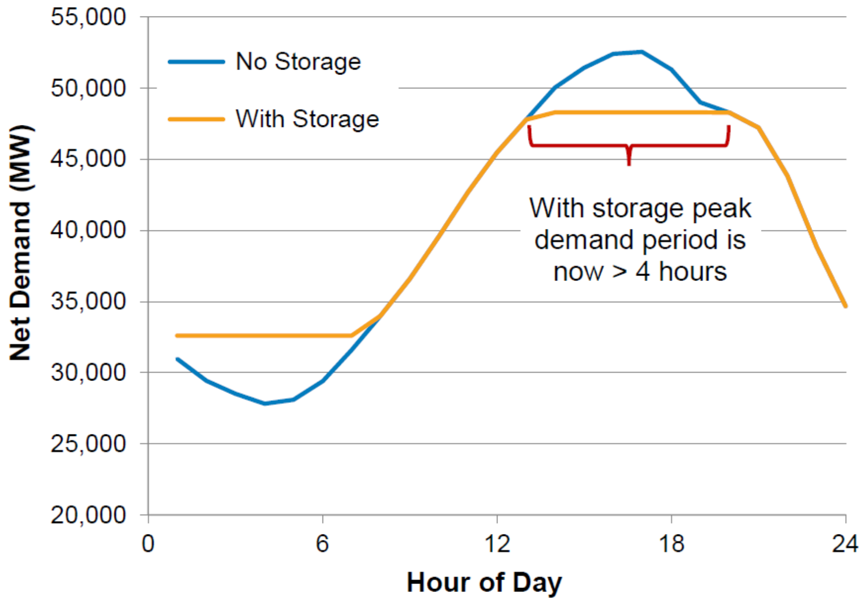
In 2018, the Federal Energy Regulatory Commission issued Order 84, which includes the requirement that all independent system operators and regional transmission organizations under the commission's jurisdiction establish duration requirements for a device to receive full capacity or resource adequacy credit, as listed in the table below.

Market Operator	Duration Minimum (hours)
ISO-NE	2
CAISO	4
NYISO	4
SPP	4
MISO	4
PJM	10

Outside PJM, all regions have adopted a requirement of 4 hours or less, and analysis has demonstrated high capacity credit for 4-hour storage in several of these regions…

Because of the greater market size for peaking capacity than operating reserves, Phase 2 has much greater potential than Phase 1. There are about 261 GW of dedicated peaking capacity in the United States, and hundreds of GW of plant retirements are expected in coming decades that include a large amount of peaking capacity. Some of these retirements are driven by policy, such as air quality and cooling water regulations, but many retirements are simply due to plant age. However, the potential for 6-hour-or-less batteries is only a fraction of this capacity due to the declining value of storage as a function of deployment. As more energy storage is deployed, the peaks become wider and energy storage is less able to meet the resulting longer periods of peak demand. At the same time, additional storage reduces the difference between on-peak and off-peak prices, thus reducing arbitrage/time-shifting benefits.

The figure below illustrates this concept in a simulated scenario where California deploys sufficient 4-hour storage to meet about 8% of annual peak demand. In this example, storage has widened the peak period to the point where the net peak is about 6 hours long, meaning a 4-hour device would receive only 4/6th of the capacity value of a conventional resource. This deployment would also substantially reduce the time-shifting (energy) value of storage.



The limits to Phase 2 are based on this declining energy and capacity value as storage is deployed. However, potentially significant synergies with deployment of solar photovoltaics (PV) could greatly increase Phase 2 storage deployments. PV could increase both the energy and capacity value of energy storage by changing the shape of energy demand, and thus offset the decline resulting from increased storage deployment…

6. Phase 3, the Age of Low-Cost Diurnal Storage

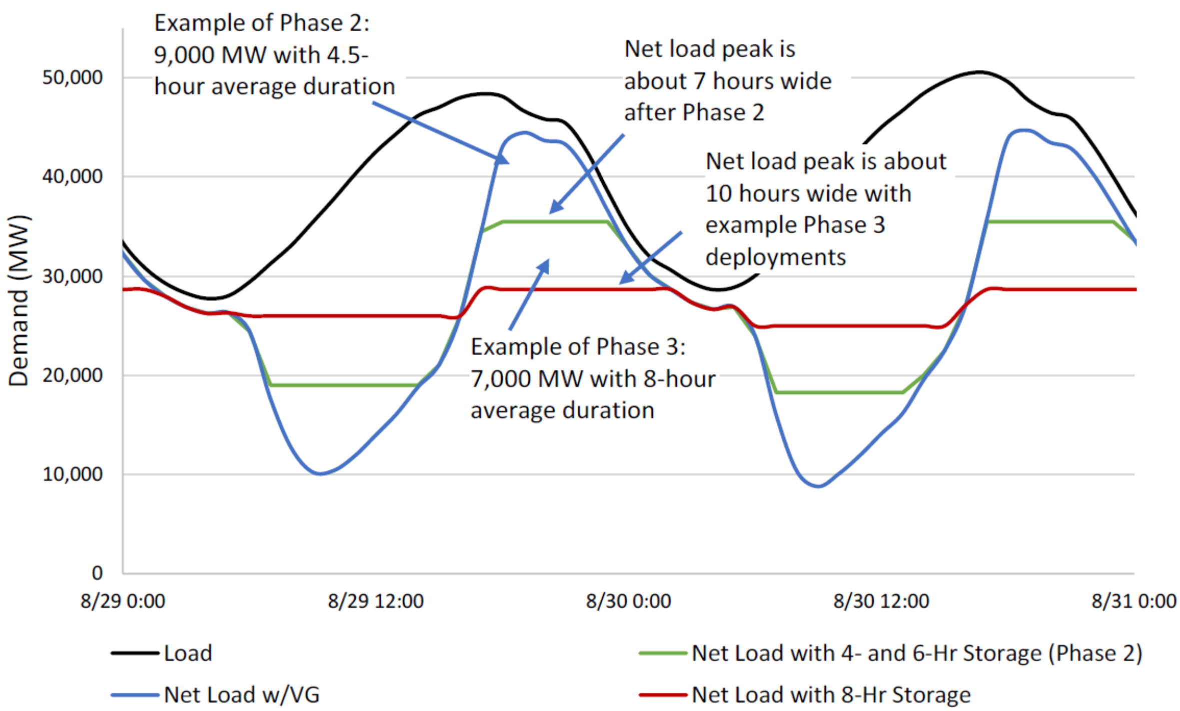
Per the definition of section 1 of SFS (per the table on page 1), Phase 3 has a duration of 4 to 12 hours. The authors of this section chose to call the "Diurnal," which means "of the day" or "during the day."

Phase 3 is perhaps the least distinct of our phases. It is characterized by a transition to the deployment of storage technologies that have some combination of lower cost or an ability to provide additional services (resulting in higher value) when compared to current lithium-ion batteries. A key element of this transition is the decline in capacity value of storage with 6 hours or less of capacity (Phase 2). Longer peak periods increase the competitiveness of technologies with lower duration related costs, including new battery chemistries, additional pumped storage, and other technology options discussed later in this subsection. The deployment that will occur in Phase 3 is more uncertain than that of earlier phases, as it depends on the degree to which storage costs decline and VRE deployments increase.

Author's comment: The above "…new battery chemistries," might include flow batteries or batteries with an architecture similar to Lithium Ion, but a much lower cost per MWh.

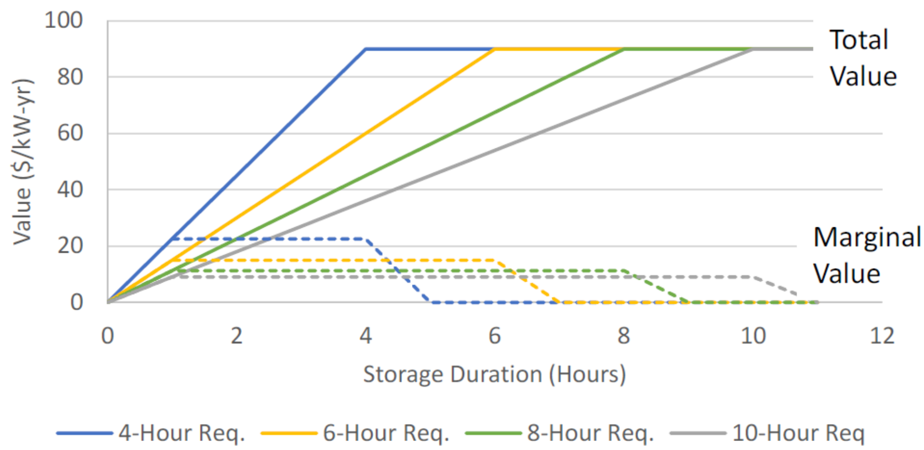
While there will likely be considerable overlap between Phase 2 and Phase 3, the key distinction in the transition to Phase 3 is the wider net peak demand periods, which require lower duration-related costs for storage to provide cost-competitive capacity services. Indicative of this transition between Phases 2 and 3, The figure below illustrates two days of high load (August 29–30) in California in a modeled scenario with a 30% annual contribution from PV. It shows the substantial narrowing of the net peak *from solar, and then the widening of the peak after addition of 4- and 6-hour storage in Phase 2, shown as the green line. The assumed 9,000 MW of battery peaking capacity has been deployed in Phase 2 with nearly full capacity credit, meaning the net load peak has been reduced by about 9,000 MW. This mix of storage has an average duration of about 4.3 hours. The net load peak is now about 7 hours long. Therefore, any additional storage with less than 7 hours of duration will need to be derated, thus reducing its value and thereby requiring reduced costs to be cost-competitive.*

Author's Comment: "VG" = "Variable Generation," in this case variable renewable generation.



The red line in the above figure shows the impact of Phase 3 deployment of another 7,000 MW of storage capacity with an average of 8 hours of duration. This deployment further reduces net load, and so provides additional firm capacity. While multiple storage power and capacity configurations could achieve this result, continued deployment of storage in Phase 3 requires significantly more energy capacity per unit of avoided conventional capacity.

Longer-duration peaks decrease the value of shorter-duration storage (i.e., produce a decline in the marginal value of incremental duration). The change in value proposition for longer net peak periods is illustrated in the figure below, which shows how the marginal value of capacity falls as the length of the peak period moves from 4 to 10 hours. Assuming an annualized value of $90/kW for firm capacity, the marginal value of each of the first 4 hours with a 6-hour duration requirement is $22.5/kW-yr per hour ($90/4). But as the requirement to achieve full capacity credit increases, this marginal value falls to $90 divided by the duration requirement (up to the duration requirement), dropping to $9/kW-yr per hour when the net load peak is 10 hours long.



The longer net peak periods in Phase 3 do not inherently require longer-duration storage. Storage plants with 6-hour or shorter duration can still provide capacity, just with a reduced capacity credit that requires a reduction in cost to offset the lower value. Alternatively, reduction in the energy component (duration) costs could allow for deployment longer-duration diurnal storage (8–12 hours) to continue to provide full capacity while further increasing the energy time-shifting value.

Section 1 of SFS continues to elaborate on the above theme, and although these are useful, I am already well over my preferred maximum length for a paper, and need to interject some content, so I will cut these off.

California is currently deploying a large amount of energy storage systems based on Lithium Ion battery technology. Per my earlier comment and content from SFS, a large majority of these have a 4-hour duration at maximum output. As soon as these are deployed they will generate maximum revenue via stacked capacity and time-shifting services -- see the beginning of section 5 (before subsection 5.1), above.

Also, some advanced flow batteries are starting to make significant inroads in the California energy storage systems market (although Lithium Ion batteries still dominate). The cost of additional duration for flow batteries is extremely low compared to Lithium Ion batteries, so the future described in this section (utility-scale PV was 13% in 2020, this model uses 30%, so probably around 2030), longer duration storage could represent an attractive market niche.

Also, all the 4-hour Lithium Ion battery energy storage systems coming on the market currently will be well into their lifetime. By derating these and providing longer duration, these could both compete with newer, less expensive technologies, and use this strategy to provide end-of-life revenue.

7. Phase 4: Multiday to Seasonal Storage

Given the long time horizon associated with Phases 2 and 3, the transition to Phase 4 is highly conjectural. Studies to date have not identified a hard technical or economic limit to RE deployment with only diurnal storage, but have also found that approaching 100% RE, the seasonal mismatch of supply and demand leads to significant challenge. This creates a potential opportunity for storage with more than 12 hours of duration, possibly extending to seasonal storage.

Alternatively, some transitions to longer-duration storage technologies might not inherently be tied to very high RE scenarios. Our four phases framework assumes most storage technologies deployed in the coming decades will continue to have a significant cost associated with duration. This cost drives the transition from shorter to longer durations, with longer durations only being deployed when the opportunities for shorter duration are largely saturated. However, many of the very long-duration storage technologies under development have very low duration-related costs. Technology breakthroughs, or dramatic cost reductions associated with deployment at scale could introduce storage with close to zero costs associated with duration and could thus result in much earlier deployment and overlap with previous phases.

Although Section 1 of SFS invests quite a bit of text analyzing phase-4, I see this as similar to stacking imaginary bricks on top of other imaginary bricks. In the interest of brevity, I’m not going there.