we acknowledge the potential for some "extra" value associated the provision of reserves as a secondary application.

Evaluating the Cost-Competitiveness of Battery 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[19] (or offset conventional capacity), which is typically measured as a value (e.g., kilowatts) or a percentage of nameplate rating (21).[20]

Only recently has there been any significant effort to evaluate the capacity credit of energy storage. Analysis of the capacity credit of storage is important, as it determines the storage duration required to provide the same level of reliable services as traditional resources. In most regions of the United States, determination of both the need for new capacity and the capacity credit applied to new resources is established by some combination of state and market regulators as well as the local market operator.

In 2018, the Federal Energy Regulatory Commission issued Order 84,1 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 Table 3 (23).

Table 3. Regional Energy Storage Duration Requirements

Market Operator	Duration Minimum (hours)
ISO-NE	2
CAISO	4
NYISO	4
SPP	4
MISO	4
PJM[21]	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 (23). However,

[19] More accurately stated, capacity credit analysis assesses the probability of a plant being available during periods of demand, which is typically during hot summer afternoons throughout most of the United States.
[20] Following Mills and Wiser (2012) (22), we use the term "capacity credit" to represent physical capacity, and we use the term "capacity value" to represent the monetary value of this capacity.
[21] PJM is in the process of updating this value based on an effective load carrying capability calculation. ("PJM Interconnection L.L.C., Docket No. ER21-278-000 Effective Load Carrying Capability Construct," PJM, October 30, 2020, https://www.pjm.com/directory/etariff/FercDockets/5832/20201030-er21-278-000.pdf.)

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analysis is ongoing, and there is some disagreement over the requirements in some regions (24); as we demonstrate later in this section, these duration requirements strongly impact the cost-competitiveness of energy storage.

The duration requirements in Table 3 (page 18) are used for planning purposes and for compensation in capacity markets or resource adequacy capacity contracts. As a result, a battery with 4 hours of capacity serving load could be compensated for providing capacity at the same rate as a traditional combustion turbine (on a dollars-per-kilowatt basis).[22] Alternatively, a 3-hour battery could be derated and receive three-quarters of the capacity payment. Thus, the capacity value of a storage resource as a function of duration has a shape like that in Figure 7. It shows the total and marginal value of capacity, assuming a 4-hour duration requirement, and an annualized capacity value of $90/kW-yr.[23]

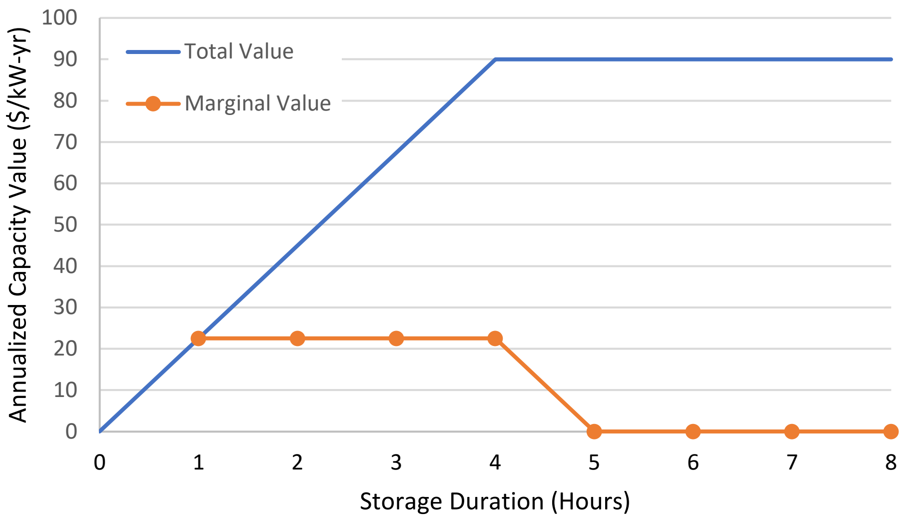

Figure 7. Value of storage providing capacity, assuming a 4-hour duration requirement and a $90/kW-yr capacity payment

Of note in Figure 7 is that the capacity value as a function of duration increases only up to the duration requirement established by the market operator or regulator; a 6-hour battery receives no more value or revenue than a 4-hour battery for this particular service in this example.
The figure also represents a system where new capacity is actually needed. In locations with sufficient capacity, the value of additional capacity can be very low, as reflected in low capacity prices in markets that approach or exceed reliability planning standards. As a result, battery storage or other sources of peaking capacity will not necessarily be cost-competitive in the near term until there is an increase in demand or sufficient retirement of existing capacity resulting in a need for new capacity.

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[22] This is simplified, as it assumes the two resources have identical outage rates.
[23] This value is roughly equal to the estimated net cost of a new entrant for a peaking combustion turbine in MISO and PJM in 2020 (25, 26). It is important to note that this value is higher than many historical capacity prices and reflects oversupply conditions.

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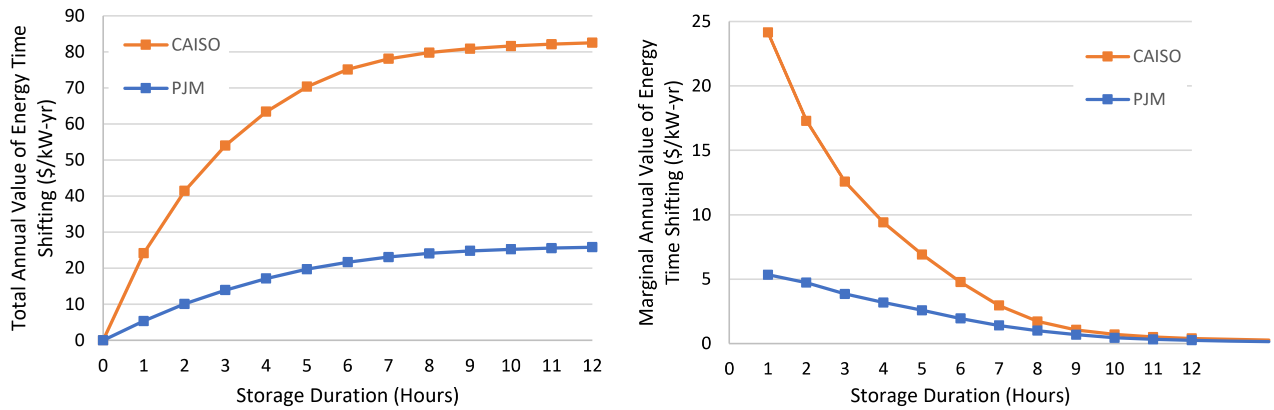
In addition to capacity, Figure 8 shows the annual value of energy shifting using an example of a hypothetical storage device dispatched into two wholesale market regions using 2019 data.[24] While the absolute value varies considerably depending on location and factors such as transmission constraints, the general trend in value as a function of duration is similar. The first hour of storage has the highest value, as it is arbitraging the largest spread in market prices. This incremental value declines rapidly as diurnal price spreads decrease, approaching—but not reaching—zero beyond about 10 hours of capacity as the diurnal variability in prices is completely arbitraged.



(a) Total value (b) Marginal value

Figure 8. Example of the total and marginal value of energy time-shifting using 2019 energy market values

A combination of the value components from Figure 7 and Figure 8 can be used to estimate a total value, shown in Figure 9a. In this example, most of the revenue is derived from capacity value instead of energy time-shifting, as demonstrated by the gray line, which represents the fraction of total value derived from capacity (assuming a 4-hour duration requirement to obtain a capacity payment of $90/kW-yr). In addition, the lower value of energy time-shifting, particularly beyond 4 hours, results in a very small incremental total value once capacity duration requirements have been met. This combination drives the economic performance of storage as a function of duration as illustrated in Figure 9b, in terms of its B/C ratio as a function of storage duration, using the cost curves for a Li-ion battery shown in Figure 3 (page 7).

[24] Analysis uses a price-taker model as described in (27) with wholesale market data from CAISO (NOISLMTR_6_N101/SDGE) and PJM (120 LOMB138 KV TR72 12/Commonwealth Edison).

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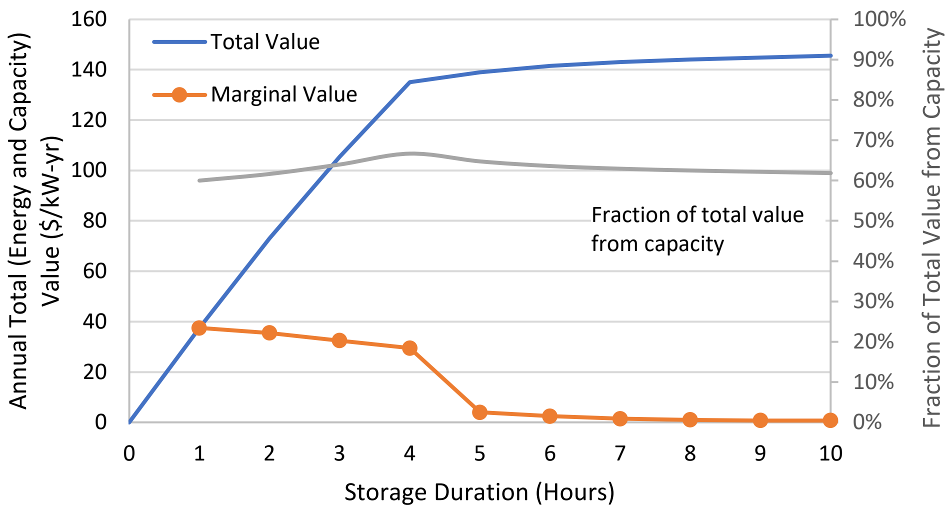
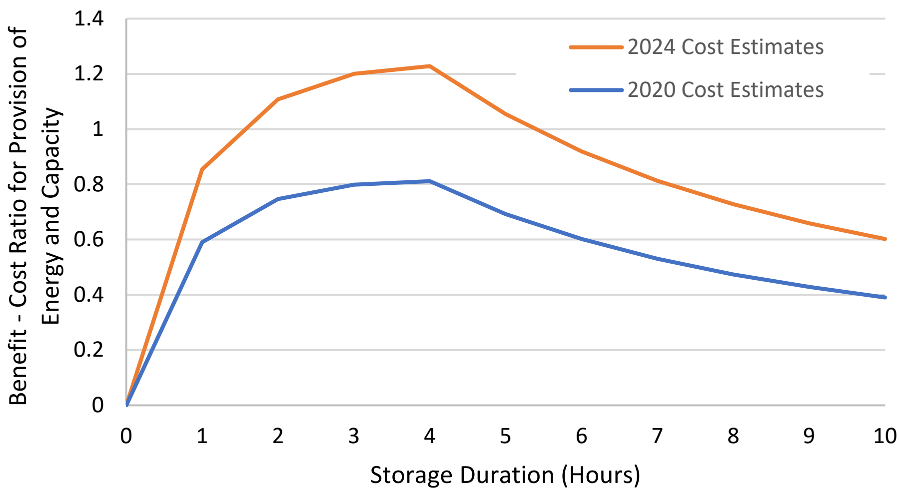


(a) Total value



(b) B/C ratio

Figure 9. Example of the total and marginal value and B/C ratio of a battery storage system providing peaking capacity using battery costs from Figure 3 and assuming a 4-hour duration requirement for full capacity value

In this example, the B/C ratios increase only up the point of a four-hour duration, at which the marginal benefits drop because the value associated with capacity falls to zero (as shown in Figure 7). Beyond 4 hours, the incremental value of additional duration is only equal to the incremental time-shifting value (Figure 8). As a result, once the minimum duration is met for a device providing a specific market service, there are rapidly diminishing returns for additional duration, suggesting transition points as storage is deployed for various applications. Using the 2020 cost estimates from Figure 3 in this example, the maximum B/C ratio is below one without additional incentives or sources of value. However, using the 2024 estimates, the B/C ratio is greater than 1 without any additional incentives.

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This simplified example is generally consistent with the literature, which generally finds a higher value associated with capacity than with energy time-shifting (28). However, this result depends on market structure. In real systems, determination of long-term capacity and energy prices (which are needed for an appropriate comparison of storage to alternatives) is very complicated given the evolving generation mix, actual need for new capacity, and market rules that limit scarcity prices that may occur during periods of peak demand (10, 29). In the extreme case of an energy-only market, physical capacity has no inherent value, and capacity-related costs must be recovered entirely through energy prices. Actually estimating the value of time-shifting (and other potential benefits such as congestion management) requires chronological simulations to determine how different resources will operate and these simulations can often reveal additional values compared to conventional resources and these can result in a higher overall value for energy storage (30).

Regardless of approach, there is a clear trend in increasing cost-competitiveness for batteries to provide peaking capacity (even without the extra values associated with operating reserves that are available before the saturation of those markets).[25] This cost-competitiveness is enhanced by the potential opportunities for deployments in hybrid configurations, where storage can be colocated with generation resources (33). The main advantage of coupling, mostly with PV, is to take advantage of the federal investment tax credit. Additional benefits can be associated with reduced costs, including siting, permitting, and some shared components. These benefits of hybrid systems can be partially offset by decreased operational and siting flexibility, but overall, the attractiveness of storage colocation is reflected in the growing queue for proposed hybrid storage projects, and a large fraction of these proposed projects include a 4-hour duration, which reflects the strong influence of the current market duration requirements, and the declining value beyond 4 hours of duration (34).

Limits to Phase 2: Declining Energy and Capacity Value, and the Impact of Renewable Energy Deployment

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 (35). 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 (36). 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.

[25] According to several market reports, 4-hour batteries are at or nearing breakeven conditions to be cost-competitive with new gas capacity. However, considerable differences remain among the various reports, and they depend on price forecasts and estimates of market revenue. Many analyses also demonstrate considerable regional variations (31, 32).

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Figure 10 illustrates this concept in a simulated scenario where California deploys sufficient 4-hour storage to meet about 8% of annual peak demand (35).[26] 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.

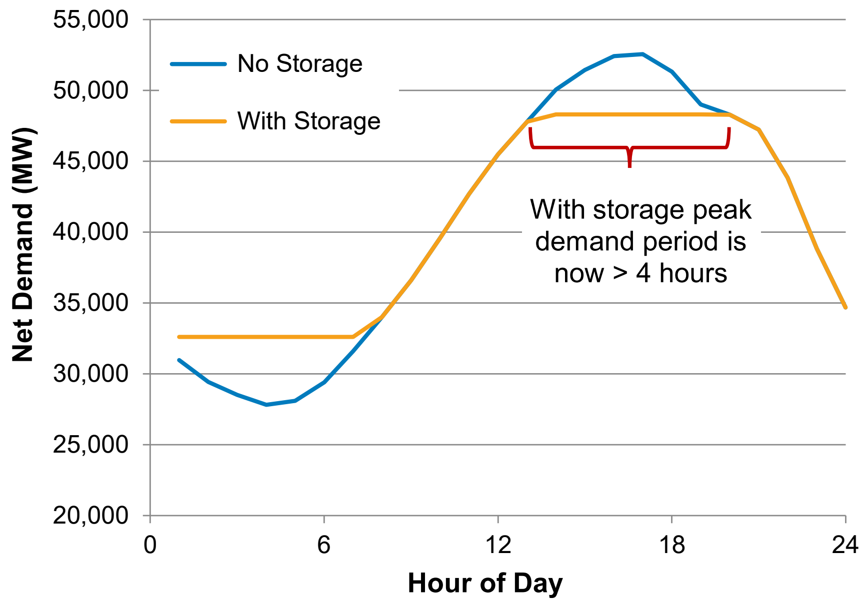

Figure 10. Simulated impact of increased 4-hour storage deployment on net load shape

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 (35).

Figure 11 illustrates how PV could narrow the net load peak and thus counteract the widening that occurs with increased storage deployment. This example subtracts simulated PV output from normal load in California on the peak day in 2013 (35). This synergy does not require PV or storage to be colocated, as the impact is system wide. However, there are some benefits of colocation, most notably the financial incentive associated with the federal investment tax credit and the reduced costs from shared infrastructure and hardware (33). As a result, much of the deployment of storage in Phase 2 may be associated with PV-plus-battery hybrid projects.

[26] We use California as an example based on early deployment of storage, and we use 4-hour storage based on its 4-hour duration requirement

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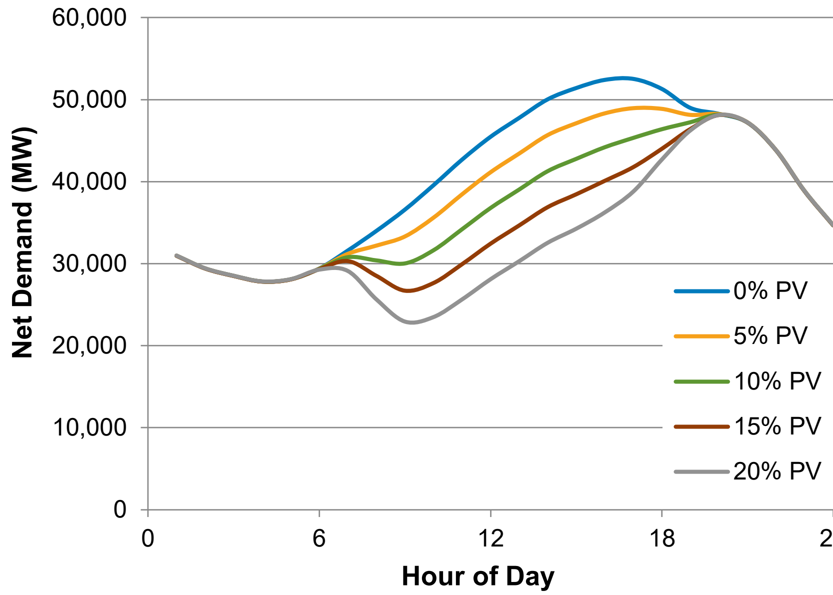

Figure 11. Change in load shape on the day with peak demand in California (2013 simulated data)

Figure 12 illustrates how PV deployment can increase the amount of 4–6 hour storage offsetting capacity requirements and extending Phase 2 considerably. Data from (35) show how much 4–6 hour storage could be deployed with high capacity credit.[27] At current levels of PV deployment, at the point where about 40 GW of 4–6 hour storage is deployed nationally, the widened peaks would start to greatly decrease the ability of additional storage to reduce the peak. However, Phase 2 opportunities increase to over 100 GW of potential at the point where PV provides about 20% to 25% of the nation's electricity.

[27] These data represent simulations of 18 regions in the United States adding various combinations of PV and 4-hour and 6-hour storage. It examines the net load in each region and identifies the amount of storage installed at the point at which net load is wider than 6 hours. These numbers are aggregated to create a national number and detailed results by each region is available (35).

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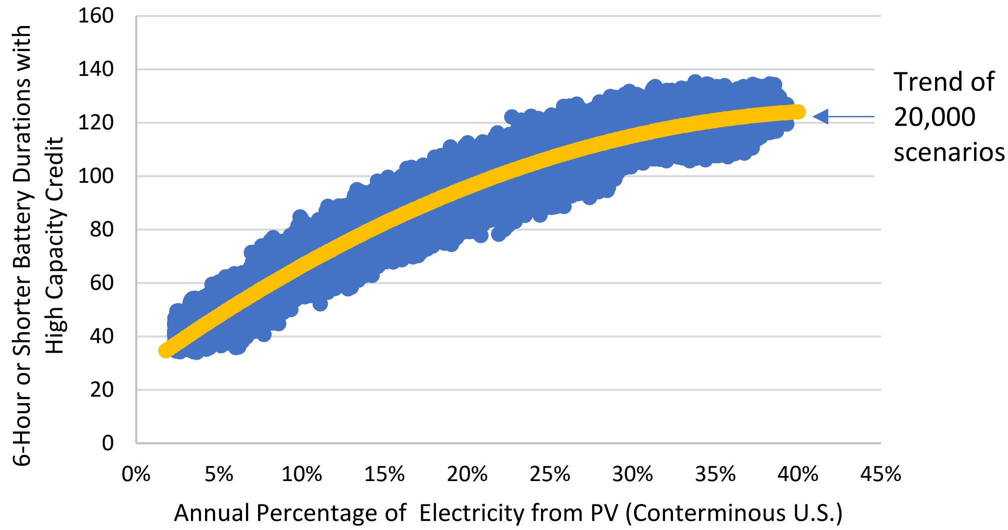

Figure 12. The potential opportunity of Phase 2: National potential of 4–6 hour batteries with high capacity credit

6 Phase 3: The Age of Low-Cost Diurnal Storage

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 section. 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.

Phase 3 Opportunities: Capacity, Energy, and Transmission Services

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, Figure 13 illustrates two days of high load (August 29–30) in California in a modeled scenario with a 30% annual contribution from PV.[28] 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.

The red line in Figure 13 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 Figure 14, 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.

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[28] Figure 2 and Figure 3 were generated using 2013 load and simulated wind and solar data and storage dispatched in the REFlex model (37).

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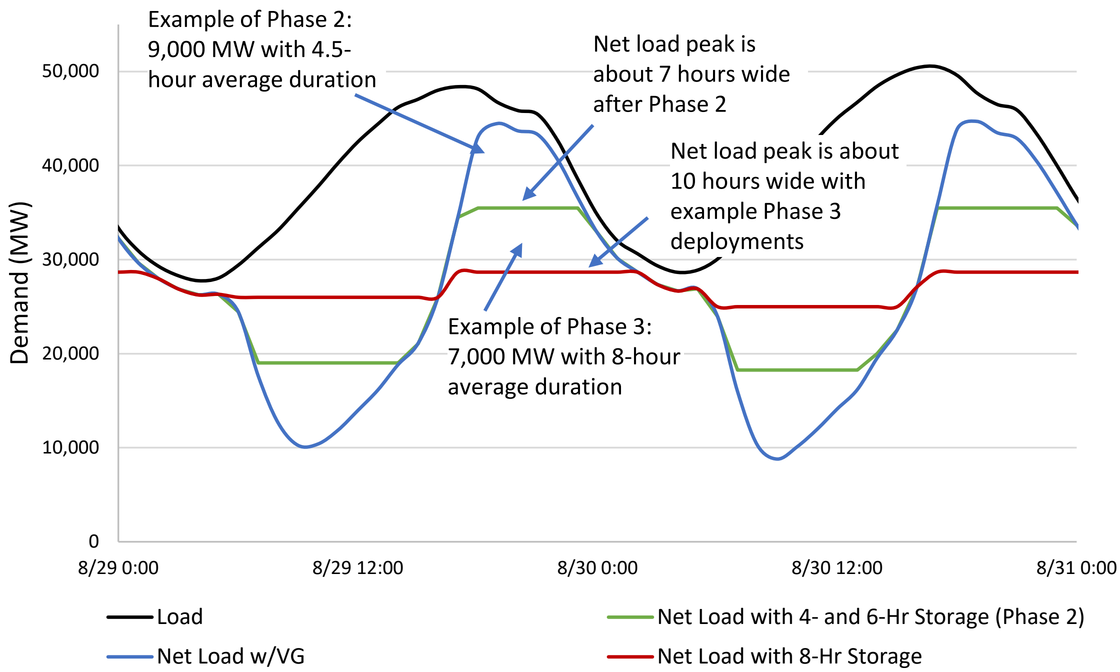

Figure 13. Example of longer-duration storage providing system capacity in California during the summer peak

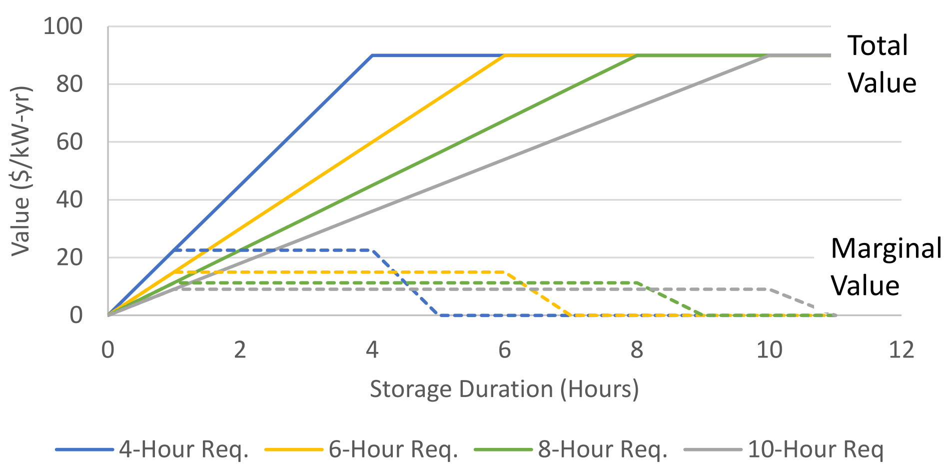

Figure 14. Annualized capacity value as a function of duration for different capacity credit duration requirements

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.

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