Energy Storage Futures, Vol 3, Diurnal Storage Economics

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February 2022

1. Introduction

The National Renewable Energy Laboratory (NREL) over the last year released a multivolume study titled “Storage Futures Study,” hereafter SFS. The high level goal of this is to model energy storage systems’ implementation out to 2050.

My current intent is to track each of these volumes with a much shorter one of my own.

Section 1 of this report focused on the types of utility-scale energy storage systems and the services that they provide to the electric grid. Our Volume 1 of Energy Storage Futures was a summary of this section, and is linked below.

https://energycentral.com/c/gr/energy-storage-futures-volume-1-types-and-services

Section 2 of this report collected and refined data to use as an input for the model of the future of storage system out to 2050. Our Volume 2 of Energy Storage Futures was a summary of this section, and is linked below.

https://energycentral.com/c/cp/energy-storage-futures-volume-2-model-input-data

Section 3 of this report evaluated the economic potential of diurnal storage. As storage systems penetrated the utility-scale storage market over the last decade, they first penetrated the ancillary services market, which was rather small, then the market for peaking power which was much larger. The next step in this process is to evaluate the economic potential diurnal storage, which is defined as storage with a duration of up to 12-hours. Our Volume 3 of Energy Storage Futures is a summary of this section.

The next two sections after section 3 will further refine the model’s inputs and section 6 will report results.

The service I hope to provide for the readers of this series is to filter out information that I feel has little chance of materially affecting the output over the period that this model simulates, and thus greatly reduce the reading-time for this summary.

2. Evolution of Storage Duration

Recent cost declines for many energy storage technologies, notably lithium-ion batteries, and increasing deployment of variable renewable energy (VRE) technologies (predominantly wind and PV) have heightened interest in storage as a grid resource. However, the total market potential for storage and the effects that storage capacity could have on power sector evolution and operations remain unclear.[1]

Estimating the market potential for storage is complex. Many grid services that storage provides, including peak shaving, energy time-shifting, and operating reserve provisions,

[1] A. Will Frazier, Wesley Cole, Paul Denholm, Scott Machen, Nathaniel Gates, and Nate Blair, NREL, “Storage Futures Study, Section 3, Economic Potential of Diurnal Storage in the U.S. Power Sector,” May 2021, https://www.nrel.gov/docs/fy21osti/77449.pdf

have declining value with storage penetration. Furthermore, these values are highly dependent on the grid system conditions and can change over time depending on the overall evolution of load, load flexibility, and the mix of generation technologies in the power sector.

Author's comment: In the above paragraph, note the "*Many grid services that storage provides… have declining value with storage penetration."* This is really important. For a good explanation of this, especially for long-duration storage, see Volume 1, linked in the Introduction, Section 6.

Storage devices also have an additional system design consideration that traditional generators do not have, namely the selection of the duration of storage investments. We define duration as the usable energy capacity (in units of watt-hours, Wh)—after accounting for losses and maximum/minimum state-of-charge—divided by the power capacity (watts, W). Duration is thus measured in hours. A 100 MW system with a 4-hour duration would be capable of storing up to 400 MWh of usable energy. Duration influences the cost of a storage device. A 6-hour 100-MW storage device will cost more than a 4-hour 100 MW storage device because of the additional energy capacity needed in the 6-hour device. The value of grid services provided by storage also grows with duration, but the cost of this additional energy capacity must be compared to this additional value and assessed on a full system life-cycle basis to determine the optimal duration of a storage investment.

Furthermore, storage is more sensitive to chronology than traditional generators because of this finite duration. The state-of-charge of a storage device is chronologically linked, and this impacts how it can be used at any given time. And unlike traditional generators, storage does not actually generate electricity, so its operation is entirely dependent on the dispatch of all other grid resources. Properly capturing these chronological considerations in large-scale models that can project market potential is a challenge.

The ability of storage to provide peaking capacity is a function of both storage duration and net load shape, where net load is defined as load minus variable renewable energy (VRE) generation. Initially relatively short durations of storage can reliably serve demand during the highest peaks, but as storage penetration grows the width of the net load peaks widen. Holding storage duration constant leads to a declining capacity credit for storage with increasing penetration. However, this decline in capacity credit can be offset by installing storage devices with longer durations but at higher cost. The shape of the net load profile also changes with investments in VRE, and this changes the techno-economic potential of providing peaking capacity from different durations of storage.

Author's comment: Note the definition of "net load" as "load minus VRE." The net load shape defines how likely peak-pricing is. If a grid has plenty of VRE (either photovoltaic (PV) and/or wind energy) at a particular time, peak pricing is not likely.

Energy time-shifting value comes from storage charging when prices are low and discharging when prices are high, so the duration of storage and shape of the energy price profile determine the possible value of this service. Price profiles can vary widely across spatial regions and change with investments in new generation, transmission, and storage resources. Low-cost generation from PV and wind drive prices down during periods of high generation. Transmission investments can reduce congestion, which can reduce the frequency and magnitude of price spikes. Energy time-shifting from storage *can raise off-peak prices and lower peak prices, and this leads to declining energy time-shifting value with increased storage penetration and an eventual techno-economic limit where the volatility of price profiles is not large enough to overcome losses from storage.*

3. Model Adjustments

For this work, we add new capabilities to the Regional Energy Deployment System (ReEDS) capacity expansion model to include detailed representation of the grid services provided by diurnal storage. Explicitly considered within the modeling framework are the relationship between these services and storage duration, the declining value of these services with storage penetration, and the evolving techno-economic implications of the changing grid infrastructure. The impacts of chronological operation on all these factors are also considered at an hourly temporal resolution…

We use the ReEDS capacity expansion model, which represents the U.S. power system in 134 regions connected by aggregated transmission corridors, to perform least-cost system wide optimization of power system retirements and investments in generation, transmission, and storage capacity through 2050. We optimize investments in the power system in sequential two-year time steps; power system operation is optimized in each biennial time-step with limited temporal resolution.

Because storage operation depends greatly on chronology, we add to ReEDS a module outside the optimization that simulates system operation at an hourly chronological resolution. Parameters related to storage—such as curtailment, storage dispatch, capacity credit of VRE and storage, energy time-shifting value, and the relationship between storage, transmission, and curtailment—are determined from the results of this hourly dispatch and used to inform the investment optimizations in the next solve year…

Author's comment: The rest of this section dived deeply into the modeling process. Although I could follow this (since I've had prior experience in modeling), I did not find it particularly useful and expect most readers would find it less so, so I didn't include it.

4. Scenarios

We use two sets of scenarios for this work. This first set of scenarios includes several different cost and price assumptions for wind, PV, natural gas, and transmission, and combines those assumptions with different projections of future battery costs to comprise a broad space of future power system conditions and identify the system conditions that influence storage adoption. The second set of scenarios restrict the services that storage can provide. These scenarios are structured to determine which services are the strongest drivers of energy storage deployment and are also performed with various battery cost projections for each to capture the relationship between service values and battery costs. These service restriction scenarios are not intended to represent real cases, but instead are used to identify key drivers of storage value. However, there may be market or other restrictions on service provision, so these scenarios do help identify the importance of monetization and compensation for various services to ensure a cost-optimal deployment of resources.

The resource sensitivity scenarios in this study focus on storage, wind, PV, natural gas, and transmission. These resource sensitivities were selected specifically because they account for most of the investments in the reference case. More, or less, investments of these resources change the dynamics of the grid composition and thus influence the *cost-competitiveness of energy storage. A total of 18 sensitivity scenarios, plus the reference case, are included in this study. The full set of these resource scenarios is shown in the table below…*

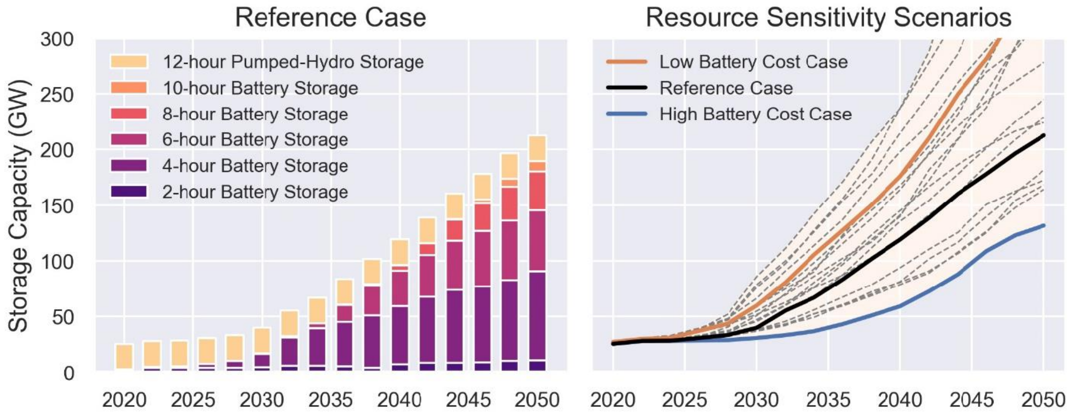
Resource Sensitivity	Battery Cost Projections
Reference	*High* Battery Costs *Reference* Battery Costs *Low* Battery Costs
Low PV Costs	*Reference* Battery Costs *Low* Battery Costs
High PV Costs	*Reference* Battery Costs
Low Wind Costs	*Reference* Battery Costs *Low* Battery Costs
High Wind Costs	*Reference* Battery Costs
Low NG Prices	*Reference Battery Costs* *Low* Battery Costs
High NG Prices	*Reference* Battery Costs *Low* Battery Costs
Low Wind and Low PV Costs	*Reference Battery Costs* *Low* Battery Costs
High Wind and High PV Costs	*Reference Battery Costs* *Low* Battery Costs
High Transmission Costs	*Reference Battery Costs* *Low* Battery Costs

The second set of scenarios used in this study—which restrict the ability of storage to provide services to the grid…

Author's comment: I did not find the second set of scenarios particularly useful, and thus did not include them, although some of the results from using these in models or analysis that draws on these models may be presented later.

5. Results: National Deployment

Battery storage deployment grows significantly through 2050 across all scenarios we examine. The figure below shows deployment by duration in the Reference Case (left) and the cumulative storage deployment in all scenarios (right). There are 213 GW (1,318 GWh) of storage by 2050 in the Reference Case, accounting for 17% of the total planning reserve margin requirement. There are 132 GW (702 GWh) and 380 GW (1,783 GWh) in the High and Low Battery Cost Cases, respectively. Across all scenarios, cumulative storage capacity in 2050 ranges from 132–679 GW (702–3242 GWh) and annual deployment of battery storage ranges from 1–30 GW in 2030 to 7–77 GW in 2050. These scenarios reach variable renewable energy (VRE) penetrations of 35%–74% in 2050 (overall renewable energy penetration of 43%-81%).



In 2020, there are 23 GW of pumped-hydro storage capacity in the United States, all of which is assumed to have a duration of 12 hours. Although new pumped-hydro storage is included in the suite of technologies assessed by the model, only new battery storage is deployed by the model across the scenarios we examine. Across all scenarios the majority of new storage deployment is 4-6 hours in duration, and the capital cost assumptions for new 12-hour pumped-hydro are higher than for 4-6 hour battery storage (DOE, 2016)...

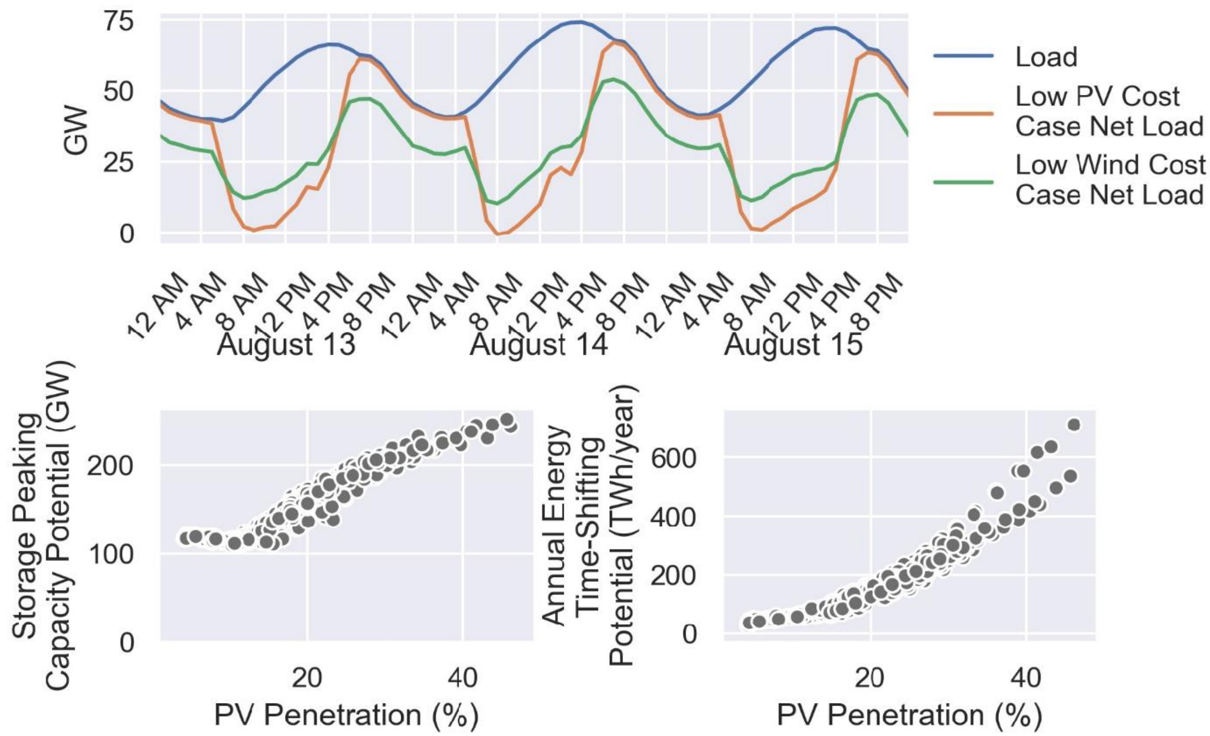
New storage deployment is initially from shorter-duration storage (up to 4 hours) and then progresses to longer durations as deployment grows. Longer-duration storage is more expensive, which aligns with the model's preference for shorter durations…

6. Results: Drivers of Deployment

To explore the drivers of storage deployment, we consider the techno-economic potential of storage services, the value of those services, and the costs of storage. The potentials are techno-economic because they depend on both technical factors (e.g., storage efficiency, load shape) and economic factors (e.g., amount of PV deployed, which generator is on the margin). The ReEDS model considers the ability of storage to independently provide three services—capacity, energy time-shifting, and operating reserves—and co-optimizes storage duration and deployment of storage alongside investments in generation and transmission.

The potential of storage services represents the upper bound on the amount of the service storage can provide but does not capture the cost of storage or services value. For operating reserves, this is simply the total amount of reserves required by the system. For capacity and energy time-shifting, the potential is more complicated and depends greatly on the net load profile, which is impacted by the amount and timing of wind and PV generation.

PV generation has a significant impact on storage potential, as illustrated in the figure below. The top panel illustrates an example how PV narrows the net peak demand periods, comparing load in California with the net load in the Low PV Cost Case (63% annual PV penetration) and the Low Wind Cost Case (40% annual PV penetration) in 2050. This narrowing of the peak and increased difference between minimum and maximum net load increases the overall techno-economic potential of storage. The bottom left panel in in this figure shows the national potential of diurnal storage (storage with 12 or fewer hours of duration) to provide peaking capacity in the United States in each year of each scenario, plotted as a function of the PV penetration.



The energy time-shifting value stream for storage is also sensitive to PV penetration. The increased difference between minimum and maximum net load also increases the potential of storage to provide energy time-shifting. The bottom right panel in the above figure shows the national annual potential for diurnal energy time-shifting in each year of each scenario plotted as a function of PV penetration. This potential is based on the optimal hourly dispatch of generation and transmission with unlimited storage available to flatten daily price profiles to within the round-trip efficiency of storage. As with peaking capacity, there is a strong relationship between the potential of storage to provide energy time-shifting and PV penetration. This potential is also sensitive to fuel price assumptions because higher/lower fuel prices increase/decrease the spread in prices.

The impact of wind or natural gas deployment on the peaking and energy time-shifting potential occurs primarily via competition with PV. High wind cost or high natural gas prices increase the relative competitiveness of PV, and increased PV deployment leads to greater potential for storage. The converse is also true.

These storage potentials can be compared to modeled economic deployments that consider the value of the services provided and costs of storage. The model determines value of each service by considering factors such as the capital and operating cost of alternative resources. In all cases, the value of firm capacity is low from the present through 2030, because throughout that period the capacity of the power system in many regions exceeds the planning reserve margin constraint enforced in the model. Over time, the value of peaking capacity increases as load grows and existing generators retire. The value of energy time-shifting also typically grows, particularly as increased PV penetration sharpens the net load profiles.

The model allows storage to provide multiple services, and because high energy prices are correlated with high net loads, these services often overlap temporally such that both *energy and capacity services can be performed simultaneously. Their combined value is often needed for storage to be a cost-optimal resource.*

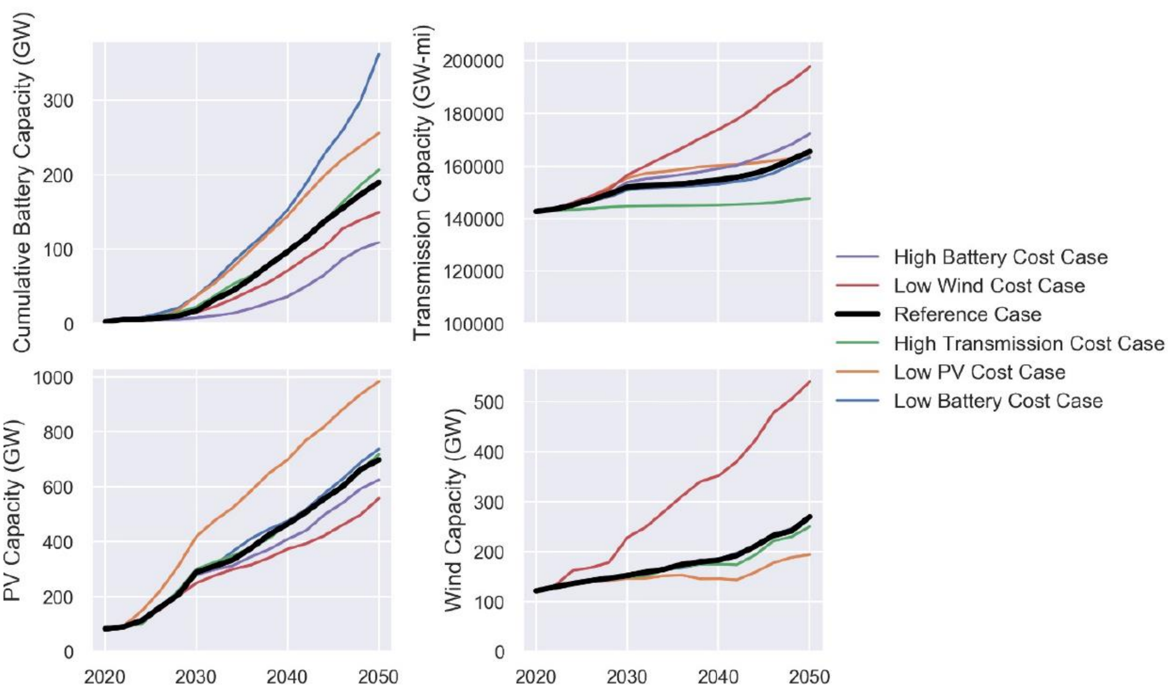
Author's comment: SFS Section 3 slices and dices the outputs from the model in many other ways. I didn't see anything else that was particularly important, so the remainder of this subsection is not included. If a reader is interested in these, SFS Section 3 appears to have a complete set of charts for these in an appendix.

7. Results: Interactions and Impact

In really complex systems where everything affects everything else it's really impossible to make generalizations. This is why computer-based models exist.

The diurnal pattern of PV generation produces the strongest interaction with storage in the modeled scenarios, but storage also interacts with other resources in the power sector, including wind and transmission.

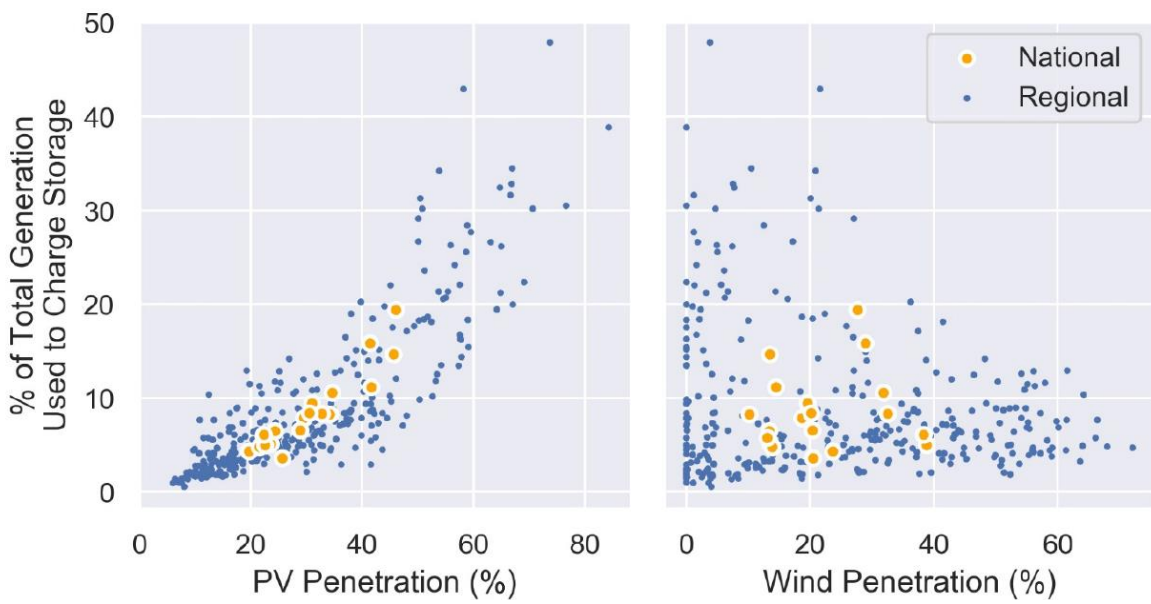
The figure below shows the cumulative capacity of storage, transmission, PV, and wind (both onshore and offshore) in a subset of scenarios. The Low PV Cost Case results in much greater PV deployment, which increases the techno-economic potential of storage as observed earlier (see figure in section 6) and also effectively reduces the cost of storage in terms of reduced duration required to get full capacity credit. This leads to significantly more storage deployment relative to the Reference Case.



Transmission and storage show limited interaction in the modeled scenarios, with the most significant correlation being between transmission and wind. ***Both transmission and storage provide flexibility to the power grid, one by shifting energy in space and the other shifting it in time.*** *Modeling results demonstrate that wind benefits more from spatial flexibility, while PV benefits more from temporal flexibility. Transmission is positively correlated with wind capacity, but additional wind does not incentivize* *additional storage, as wind frequently does not change the net load shape in a way that increases storage peaking capacity potential.*

The synergies of diurnal storage and wind are relatively small compared to PV. The Low Wind Cost Case has significantly more wind deployment than the reference case, and this offsets some PV deployment. Because of the strong correlation between storage potential and PV penetration, the decrease in PV deployment in this scenario leads to a decrease in storage investments relative to the reference case because lower PV penetrations mean lower techno-economic potentials for storage).

The role of storage and its synergies with PV relative to wind can also be observed by examining the amount of energy cycled through storage. The figure below shows, both nationally and regionally for each scenario in 2050, the percent of total generation that is used to charge storage plotted against the PV and wind penetration. The amount of generation used to charge storage in 2050 nationally is 7% in the Reference Case and ranges from 4% in the High PV Cost Case to 19% in the High NG Price and Low Battery Cost Case. While large amounts of wind and PV are deployed across these scenarios as part of the least-cost solution, the diurnal generation profile from PV enables further storage deployment. Under scenarios of high wind deployment, wind reaches high penetrations without significant storage deployment.



The final SFS subsection was "Discussion and Future Work," and this was relatively short, and contained some interesting discussion, but I really did not see any compelling insights. However the first part of SFS Section 3 did contain many compelling insights. I believe the most important of this is that PV and diurnal storage will be tightly linked in the future, and Wind and diurnal storage, not so much.

The above surprised me. Before reading and considering this SFS section, I would have guessed that both renewable sources' deployment would show considerable correlation with storage. My argument would be that weather forecasts have been getting increasingly accurate lately, including wind velocities for the next few days. Given this information (even assuming that the accuracy will not increase in the future, which is silly) I would have guessed that both renewable sources' deployments would have induced increased storage use.