Storage Effectiveness in Enabling Variable Generation and Avoiding Fossil Emissions

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About HydroWIRES

In April 2019, the U.S. Department of Energy Water Power Technologies Office launched the HydroWIRES Initiative[1] to understand, enable, and improve hydropower and pumped storage hydropower's (PSH's) contributions to reliability, resilience, and integration in the rapidly evolving U.S. electric system. The unique characteristics of hydropower, including PSH, make it well suited to provide a range of storage, generation flexibility, and other grid services to support the cost-effective integration of variable renewable resources.

The U.S. electric system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. Though increasing deployment of variable renewables such as wind and solar have enabled low-cost, clean energy in many U.S. regions, it has also created a need for resources that can store energy or quickly change their operations to ensure a reliable and resilient grid. Hydropower (including PSH) is not only a supplier of bulk, low-cost, renewable energy but also a source of large-scale flexibility and a force multiplier for other renewable power generation sources. Realizing this potential requires innovation in several areas, including understanding value drivers for hydropower under evolving system conditions, describing flexible capabilities and associated trade-offs associated with hydropower meeting system needs, optimizing hydropower operations and planning, and developing innovative technologies that enable hydropower to operate more flexibly.

HydroWIRES is distinguished in its close engagement with the DOE national laboratories. Five national laboratories—Argonne National Laboratory, Idaho National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—work as a team to provide strategic insight and develop connections across the HydroWIRES portfolio as well as broader DOE and national laboratory efforts such as the Grid Modernization Initiative.

Research efforts under the HydroWIRES Initiative are designed to benefit hydropower owners and operators, independent system operators, regional transmission organizations, regulators, original equipment manufacturers, and environmental organizations by developing data, analysis, models, and technology research and development that can improve their capabilities and inform their decisions.

More information about HydroWIRES is available at energy.gov/hydrowires.

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[1] Hydropower and Water Innovation for a Resilient Electricity System (HydroWIRES)

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Abstract

A common question in grid integration work is, “What is the role of storage in integrating variable renewable generation?” This paper presents a methodology that investigates this question for 2-, 6-, and 10-hour storage for 134 model balancing areas in the contiguous United States. The scenario considered is the role of storage in transitioning to a low-carbon grid (95% carbon reduction by 2035) in the period spanning 2022–2036. The team investigated the marginal quantity of variable generation (VG) that could be supported and the unmitigated fossil generation avoided per megawatt of storage deployed. The main findings were (1) the results are highly sensitive to location (e.g., storage in more promising areas can support over twice as much VG as in a typical area), (2) longer-duration storage (6-hour and especially 10-hour) has significantly more value in terms of its ability to displace more fossil generation per unit of storage added, and (3) as the amount of renewable energy in a system increases, the ability of the next incremental unit of storage to reduce emissions diminishes. The reason for this last point is that the fossil generation that remains in a high-renewables system is kept primarily for reliability purposes and therefore generates few emissions. The paper also presents a graphical depiction of storage and VG complementarity that helps stakeholders better understand the relationship and relative importance of energy and firm capacity in the replacement of fossil generation.

1 Introduction

In this paper, we investigate the relationship between energy storage and variable generation (VG) and how they can be used to replace fossil-fired power generation technologies[1] and avoid the associated emissions. Unlike fossil generation, VG relies on variable resources like wind and solar—but the timing of these resources does not always match system needs, which creates challenges in terms of both when energy is delivered and the reliability of that delivery. These challenges are typically addressed in one of two ways: (1) by pairing VG with storage to provide firm, time-shiftable energy[2] or (2) by building additional VG throughout an interconnection so that adequate amounts of VG are always available.[3] The choice of how much to build of each (storage and VG) is typically an economic one. In this work, we focus on the first case—investigating the role of storage in bringing renewables onto the grid.

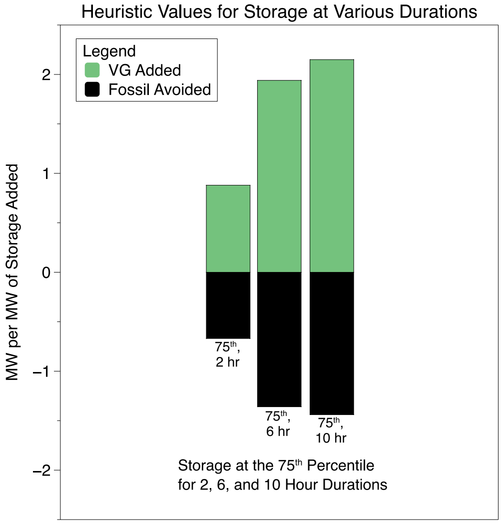

Figure 1. An example of VG supported and fossil generation avoided at various storage durations

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[1] Throughout this paper, when we refer to fossil technologies or fossil-fired generation, we are referring to generation without carbon abatement technologies.

[2] The firming can be local (e.g., solar photovoltaics paired with batteries) or at the balancing authority level (e.g., wind supported by storage or other firm capacity devices).

[3] The idea is that if you build enough of it, somewhere the wind will be blowing or the sun will be shining.

Key to successful replacement of fossil generation is to structure the exchange such that both supply needs (energy demand) and system reliability needs (firm capacity) are met. Figure 1 shows an example of such an exchange in a low-carbon system, where the addition of 1 megawatt (MW) of 10-hour-duration storage when paired with 2.2 MW of VG can be used to avoid 1.4 MW of fossil generation.

Energy needs can be thought of in terms of an energy balance, where the energy provided by the VG and consumed by the storage system[4] need to be greater than or equal to the energy provided by the fossil generation being replaced. Mathematically, this relationship can be expressed as:

$$Energy_{VG} + Energy_{stor} \geq Energy_{fossil} \tag{1}$$

where VG, stor, and fossil respectively refer to variable generation (i.e., combined wind and solar), storage, and fossil-based generation.

Reliability can be considered in a similar manner. One aspect of a system's reliability is its firm capacity, which in simple terms can be thought of as a measure of a generation source's ability to meet system needs during times of stress.

With firm capacity as the metric, the "reliability" balance can be written as:

$$Firm\ Capacity_{VG} + Firm\ Capacity_{stor} \geq Firm\ Capacity_{fossil} \tag{2}$$

In this case, the firm capacity of the VG and storage combination must meet or exceed the firm capacity of the fossil generation that is being replaced. These two equations, when used with measured or modeled power system operation results, provide an estimate of storage and VG mixes that can be used to replace fossil-fueled generation for a given scenario for each location (i.e., balancing area or region) and point in time, as shown in Figure 2. Feasible VG and storage combinations are those that provide sufficient energy (i.e., those to the right of the green energy balance line) and adequate firm capacity (i.e., those above the purple firm capacity balance line).

For the data set underlying this work, we chose NREL's Mid-Case/95% Carbon Reduction by 2035 scenario (Cole et al. 2021; known going forward as the Mid-Case/Low-Carbon scenario).[5] This scenario is representative of the administration's goals. It provides an ideal opportunity to investigate how storage of various durations performs in a low-carbon but otherwise "business-as-usual" setting and how the trajectory of this buildout—which includes new storage, generation, and transmission as well as unit retirements—influences the calculations. Finally, we focused on the least-cost technology mix of storage and VG that satisfied the equations[6] (the intersection of the two equations, shown by the circle in Figure 2).

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[4] Storage is a net consumer of energy, and the $Energy_{stor}$ value in Eq. (1) is a negative value.

[5] The Mid-Case/Low-Carbon scenario relies on reference fuel costs, demand growth, and constraints. Policies, except for the low-carbon overlay, are policies in effect as of June 2021. Midrange technology costs and innovation are assumed.

[6] While other mixes are certainly feasible, it is storage's ability to keep renewables' costs competitive that is key to "enabling" VG.

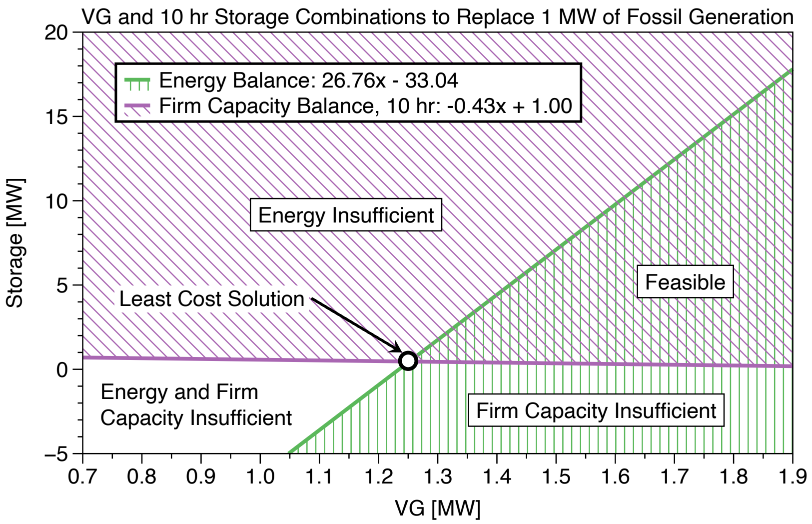


Figure 2. An example of the variable generation and storage relationship for replacing 1 MW of fossil generation with storage and variable renewable energy

Key findings are presented in the following section, primarily from the perspective of carbon reduction (e.g., we rank results according to how much VG can be paired with a megawatt of storage). Additional information about the Mid-Case/Low-Carbon scenario and details of the calculations can be found in the Appendix.

2 Key Findings

Results are presented in terms of the role of storage (when paired with VG) in replacing fossil generation, with an emphasis on how longer-duration storage such as pumped storage hydropower (PSH) helps meet low-carbon goals. Storage at three durations—2, 6, and 10 hours—was investigated, and the results are presented from three perspectives:

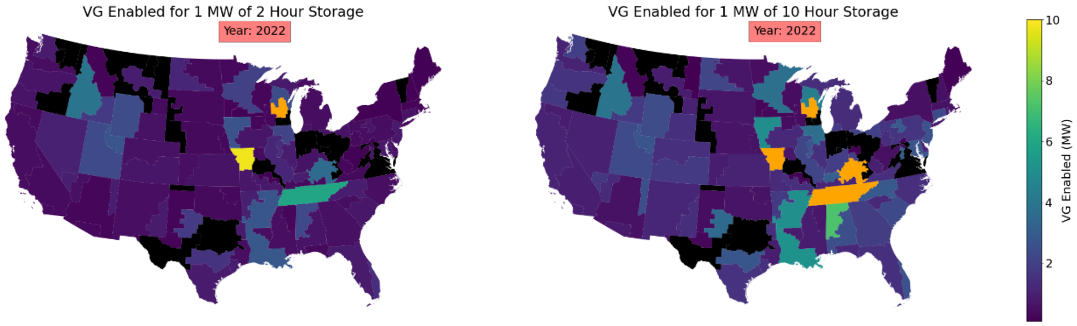
- Effects of storage duration in VG pairing at the balancing authority level (Section 2.1)
- Storage and VG's role in avoiding emissions, from a regional and storage duration viewpoint (Section 2.2)
- The role of PSH in providing firm capacity (Section 2.3).

Also of note is that results are presented at the balancing authority level, which is typical for studies that seek to better understand the role of storage in reliability for a high-renewables/low-carbon grid.

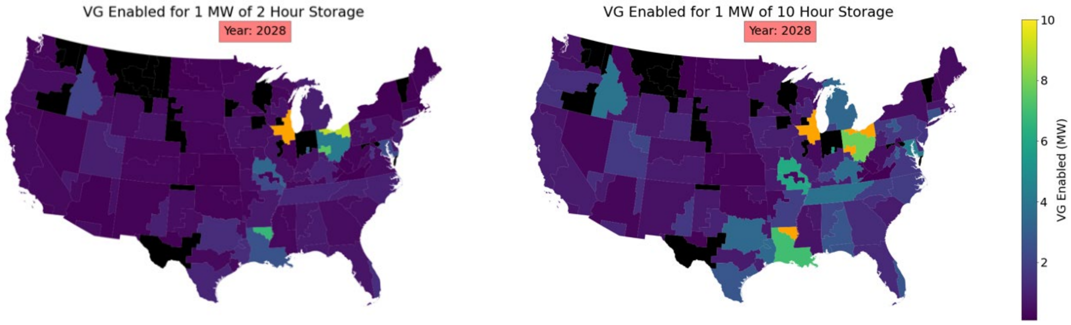
2.1 Variable Generation by Location and Storage Duration

To get an overview of how geographic location and storage duration affect the amount of VG that would be required to replace fossil generation in a region, we plotted outcomes by balancing area and storage duration (Figure 3). The maps allow the reader to quickly identify how needs vary throughout the country. Areas where fossil generation is still used extensively for power generation require larger amounts of variable renewable energy production capabilities to offset the fossil generation.

2022



2028



2034

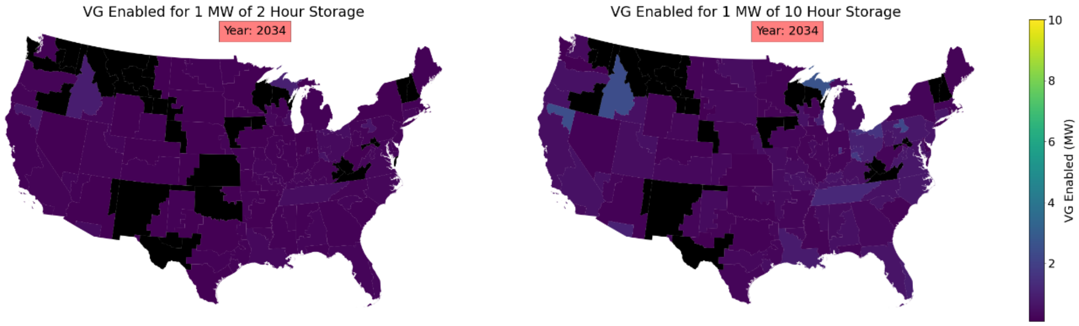


Figure 3. Variable generation necessary per megawatt of storage added to offset fossil generation. Two-hour-duration and 10-hour-duration storage are displayed. Note that locations shown in orange are above the 10-MW limit.

2.2 The Role of Storage and Variable Generation in Avoiding Emissions by Region

This section discusses how results vary by location and time. Here, the results from 134 balancing areas were rank-ordered according to how much VG was paired per unit of storage, and the results for the 60th, 75th, and 90th percentile regions were plotted. In examining Figure 4, two trends become clear. First, across all study years, location matters. The new storage in the 90th percentile region supports more than double the amount of VG and associated emissions avoidance in the 60th percentile region. Regions with higher emissions tend to have higher fossil capacity factors and higher capacity factor renewables (e.g., more wind than solar). Although we calculate some adjacent regions to have significant differences in VG enabled or emissions displaced, transmission between regions could mean that regions neighboring high-impact storage regions may also have high impact.

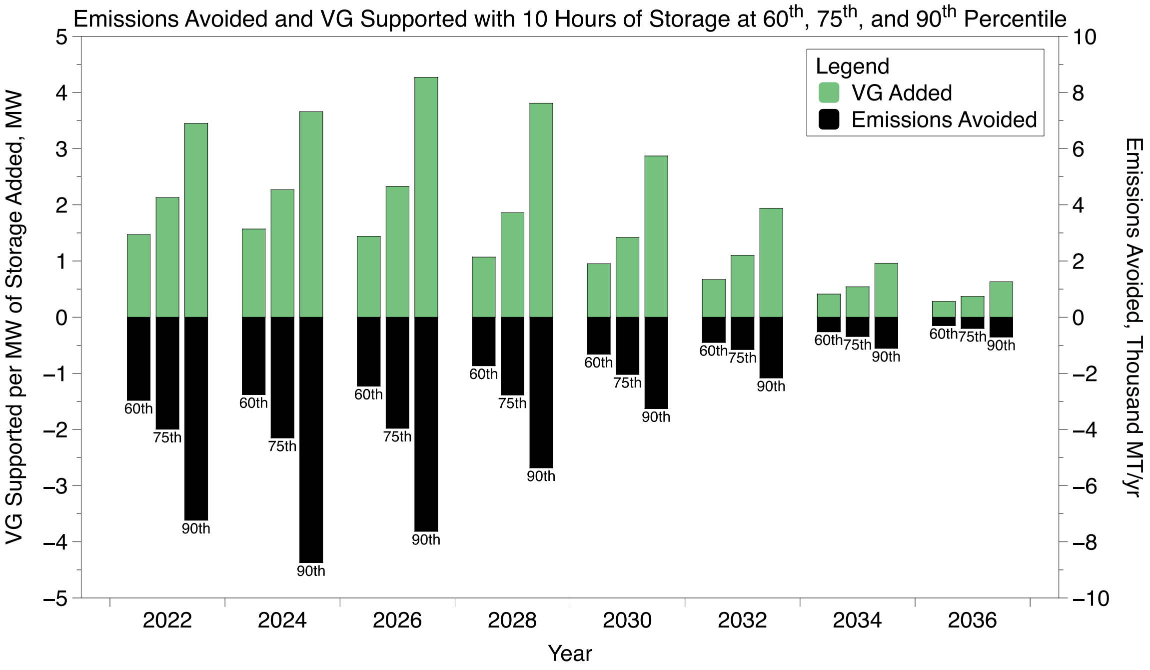


Figure 4. Marginal variable generation supported and emissions avoided at the 60th, 75th, and 90th percentiles

Second, the impact of adding storage diminishes with each new marginal unit of storage added over time. Part of the reason for the decline is that there will be less fossil generation to remove in later years, and thus the amount of emissions avoided per next unit of storage is incrementally less. This is particularly noticeable in regions where there is already active storage. However, another factor that contributes to the decline is that the marginal value of the capacity of storage declines as additional storage is added—this will be discussed in the next section.

2.3 Variable Generation and Emissions Avoided by Storage Duration

We also investigated how storage duration affects how much fossil generation could be avoided per megawatt of storage added. We considered two different approaches. First, we looked at how storage duration affects the amount of VG and storage necessary to offset 1 MW of fossil capacity. As shown in Figure 5, the amount of 10-hour storage necessary to replace 1 MW of fossil generation is about a quarter of what would be required with 2-hour storage (0.91 MW vs. 3.81 MW), and the reduction in required VG is about half (0.28 MW vs. 0.5 MW) in this example. While the least-cost pairings (i.e., the point of intersection) differ by scenario assumptions and year, the pattern is the same—with longer-duration storage, less storage and VG capacity are necessary to offset fossil-fired generation.

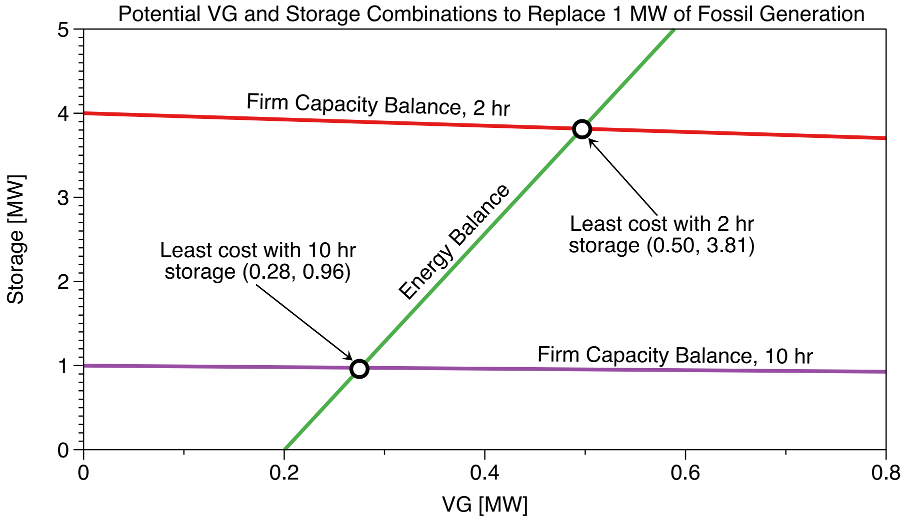


Figure 5. An example of how storage duration affects the solution space[7]

Next, we compared the contributions of storage duration over the study horizon (2022–2036). We chose a region at the 75th percentile to represent investment in regions where we would expect storage to have an above-average impact in terms of VG pairing and emissions avoidance.

Figure 6 shows that, as with earlier results, storage contributes most in terms of VG support (MW) and emissions avoidance (megatons per year [MT/yr]) in the near term. In 2026 in the 75th percentile region, 1 MW of 10-hour-duration storage supports 2.3 MW of VG, but that value declines to 0.4 MW by the end of the study period. This makes sense intuitively in that the fossil-fueled generation that remains in later years is there to provide firm capacity and is only occasionally used for generation. Avoided emissions follow a similar trend, dropping from 4,305 MT/yr in 2024 to 405 MT/yr by 2036—more than a tenfold decrease (again, less fossil-based generation means less emissions to offset).

In the next section, we take a closer look at the role of capacity in avoiding fossil generation and its associated emissions.

2.4 The Capacity Value of Pumped Storage Hydropower

In later years of the study period, fossil generation provides little energy but instead remains to provide capacity value, which is apparent when comparing Figure 6 and Figure 7. Figure 7 shows that at the peak in 2026, the combination of 2.3 MW of VG and 1 MW of 10-hour storage helps avoid 1.6 MW of fossil capacity. While the ability to displace fossil capacity does decline

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[7] For Figure 5, we removed the cross-hatching to make the figure easier to read. Please refer to Figure 2 to understand which regions are energy insufficient, firm capacity insufficient, etc.

in later years, the decline is far less than what is noted in terms of emissions avoided (it drops to 1.0 MW, a decline of 33%, the majority of which is coming from the loss of capacity value contribution from the VG rather than a decline in the capacity value offered by the storage). Said simply, in later years, the value of storage is in the firm capacity that it provides (10-hour storage can provide almost a one-for-one swap with fossil generation in terms of capacity value).

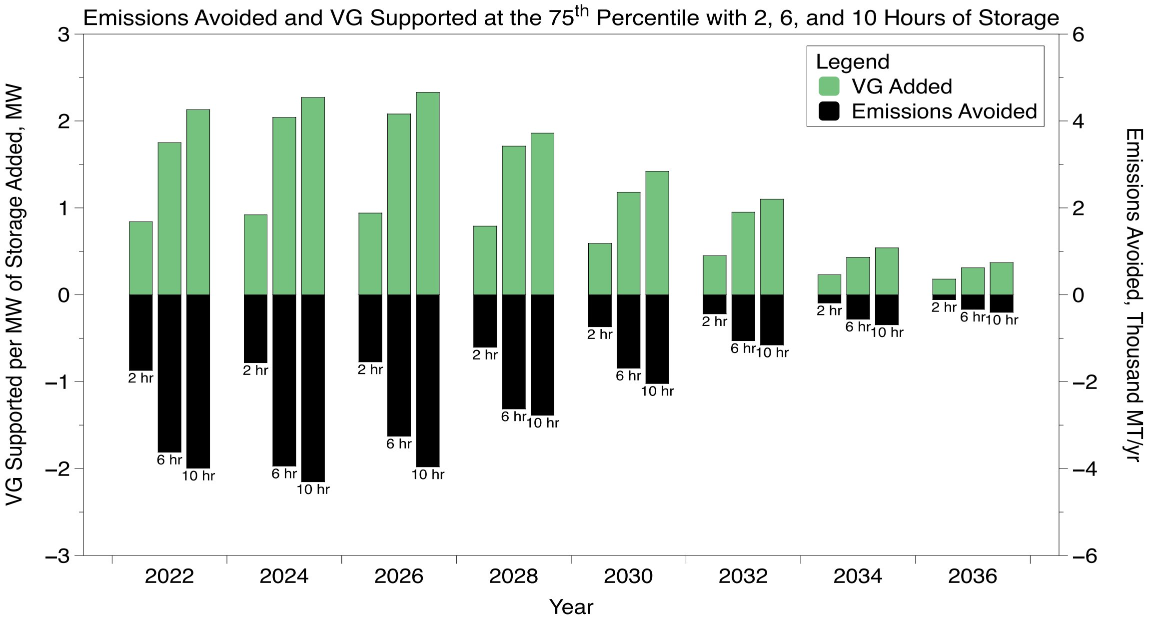

Figure 6. Variable generation supported and emissions avoided by duration

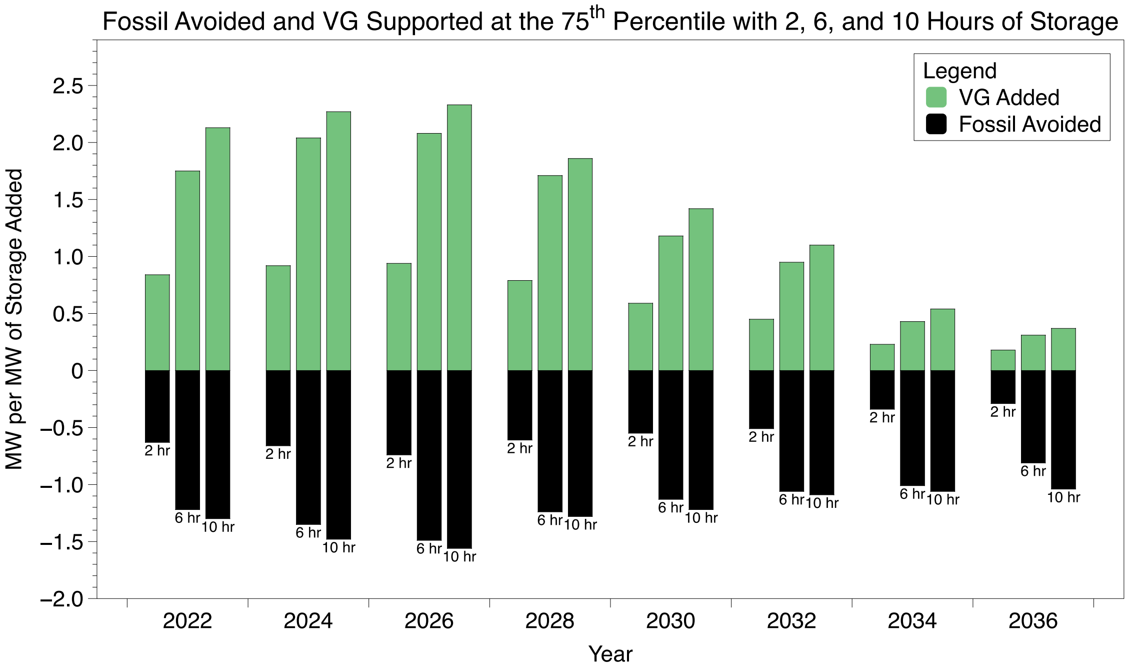

Figure 7. Variable generation enabled and fossil generation avoided as a function of storage duration

Also note that while the 6-hour and 10-hour storage displace similar amounts of fossil capacity for most of the study duration, by 2036 the 10-hour storage has 28% higher capacity displacement. The reason for this is that even the 6-hour storage markets are beginning to saturate late in the study period, and the capacity value of 6-hour storage has started to drop. These findings are consistent with NREL's recent Storage Futures Study work, which also found that the capacity value of shorter-duration storage declined for low-carbon systems with high VG contributions (Frazier et al. 2021).

2.5 Heuristics for Estimating Storage Value for Enabling Variable Generation and Avoiding Emissions

Finally, to help make these findings easier to use, Figure 8 provides heuristic values that can help explain how storage contributions vary by geographic location (i.e., at different percentiles) as well as how storage duration affects the amount of variable generation enabled and emissions. These plots were created by averaging values from 2026, 2028, and 2030 and are designed to be representative of expected gains associated with longer-duration storage projects while considering expected construction and commissioning times.

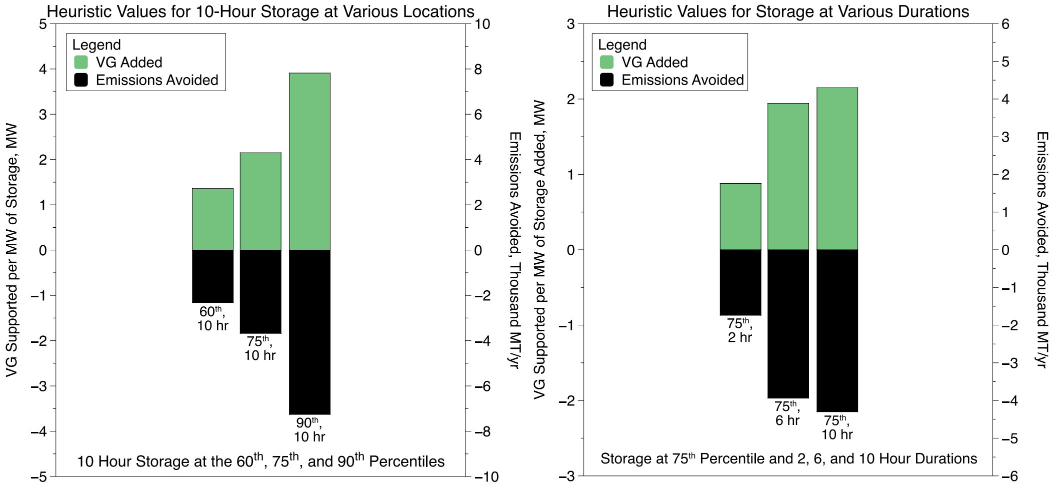

Figure 8. Heuristics of variable generation supported and emissions avoided for (left) pumped storage hydropower at various locations and (right) storage at various durations

3 Conclusion

We conducted a detailed study that investigated how storage at different locations and durations can help integrate variable generation and subsequently displace carbon emissions from fossil-fired generation. We analyzed the marginal impact of storage in a single trajectory toward a low-carbon future. Different trajectories of storage, generation, and transmission buildout would lead to differences in the values. Each calculation is a single-year snapshot of the marginal unit and not an estimate of its lifetime emissions impact. A summary of the findings of the study are:

- The ability of the combination of variable renewables and storage to displace fossil generation varies markedly by region, and locating storage in more promising regions[8]

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[8] In this context, "more promising" refers to the gains made in terms of VG supported and emissions removed.

allows the support of significantly more wind and solar per megawatt of storage added (regions at the 90th percentile support twice as much renewable generation as regions at the 60th percentile).

- While 2-hour storage has value for both integrating renewable generation and avoiding emissions in the near term, 6- and 10-hour storage have significantly more value in terms of their ability to displace more fossil generation per unit of storage power; this difference persists throughout the study years.
- As the amount of renewable energy in a system increases, the ability of the next incremental unit of storage to reduce emissions diminishes because the fossil generation that remains generates few emissions (they are kept primarily for reliability purposes—i.e., providing firm capacity—and thus used infrequently).
- In the low-carbon/high-renewables system studied, 10-hour storage (e.g., PSH) maintained its capacity value better than that of the shorter-duration storage over the study period, with 1 MW of 10-hour storage being worth more than 4 times as much as 2-hour storage in terms of capacity value in later years.

The goal of this work was to create some relatively simple metrics and visualizations backed by detailed modeling. Our hope is that these findings will help stakeholders better understand the role of storage in VG integration as many parts of the country strive to meet reduced carbon goals.

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Appendix

This section is provided for readers who would like to better understand how the reported results were obtained. Both background information on the Mid-Case/Low Carbon scenario and calculation methodology are supplied.

Mid-Case/Low Carbon Scenario

In NREL's *2021 Standard Scenarios Report* (Cole et al. 2021), the team investigated a scenario/carbon policy combination that closely approximates the Biden administration's plan for net-zero carbon by 2035. The scenario, known as the Mid-Case/Low-Carbon scenario, represents expected grid buildout under business-as-usual technology costs, fuel costs, demand growth, and resource constraints. When combined with a 95% reduction in carbon by 2035 policy implementation, it provided an ideal opportunity to investigate how the implementation of a near-zero carbon policy in an otherwise "business-as-usual" scenario would affect grid buildout.

Specifically, the 2021 Mid-Case/95% reduction in carbon by 2035 results provided biannual projections of grid buildout (and generator retirement) by technology type for 134 model balancing authorities along with supporting metrics such as installed capacity, capacity factor,[9] and capacity value[10]—all values that are useful for estimating storage's role in variable generation buildout and fossil generation avoidance.

Methodology

The annual energy provided by each technology (or technology class, e.g., variable generation) can be represented in terms of its capacity factor, CF_i, and capacity, Cap_i, as:

$$Energy_i = 8760 \bullet (CF_i \bullet Cap_i) \tag{3}$$

Substituting into Eq. (1), rearranging, and using average values for each technology class, the energy balance becomes:

$$8760 \bullet (CF_{fossil} \bullet Cap_{fossil} - CF_{VG} \bullet Cap_{VG}) = Annual\ Energy_{stor} \tag{4}$$

Likewise, firm capacity can be thought of in terms of capacity value, CV_i, and capacity, Cap_i:

$$Firm\ Capacity_i = CV_i \bullet Cap_i \tag{5}$$

Allowing the "reliability" balance (Eq. (2)) to be rewritten:

$$CV_{fossil} \bullet Cap_{fossil} - CV_{VG} \bullet Cap_{VG} = CV_{stor} \bullet Cap_{stor} \tag{6}$$

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[9] Capacity factor is the unitless ratio of actual electrical energy output over a given period (usually 1 year) to the theoretical maximum electrical energy output over that period.

[10] Capacity value (also known as capacity credit or CC) is the fraction of the installed capacity of a power plant that can be relied upon at a given time (typically during system stress). It is a unitless value that is frequently expressed as a percentage of the nameplate capacity.

Equations (4) and (6) can be rewritten in matrix notation as:

$$\begin{bmatrix} CF_{fossil} & -CF_{VG} \\ CV_{fossil} & -CV_{VG} \end{bmatrix} \begin{bmatrix} Cap_{fossil} \\ Cap_{VG} \end{bmatrix} = \begin{bmatrix} Energy_{stor} \\ CV_{stor} \bullet Cap_{stor} \end{bmatrix} \tag{7}$$

The two unknowns in Eq. (7) are the capacity of fossil generation that can be avoided, Cap_{fossil}, and the capacity of the variable generation, Cap_{VG}, that can be enabled for each unit of storage, Cap_{stor}, added (for the purposes of these calculations, 1 MW was assumed since we are investigating the incremental effects of storage).

All other values are either available from the Standard Scenario results (e.g., capacity factors and capacity values for fossil, VG, and storage) or can be easily estimated (e.g., the energy provided by a typical PSH plant per megawatt of capacity) as described below.

The following values were obtained from the Standard Scenario results:

- CV_{fossil} is the blended capacity value of the fossil fleet and is unitless. This value was derived from the Regional Energy Deployment System (ReEDS) firm capacity and capacity information.
- CV_{VG} is a blended capacity value representative of the recently installed variable generation (i.e., "marginal" values for wind and/or solar) and is unitless. The underlying values (i.e., the wind and solar capacity values) were calculated by ReEDS based on 7 years of hourly wind, solar, and load data.
- CV_{stor} is the capacity value of new storage and is unitless. Note that this value varies both with storage duration (the capacity value of 10-hour storage is usually higher than that of 2-hour storage) and with buildout (the capacity value of storage declines as the storage market becomes saturated, the net load shape/peak gets wider, and it takes more and more hours of storage to get firm capacity). This value was calculated by ReEDS based on 7 years of hourly wind, solar, and load data for the given generation mix in each year and region.
- CF_{fossil} is the blended capacity factor of the fossil fleet and is unitless. This value was derived from the ReEDS generation and capacity information.
- CF_{VG} is the blended capacity value of recently installed variable generation and is unitless. This value was derived from the ReEDS generation and capacity information.

The following values were assumed:

- Cap_{stor} is the amount of storage to be added. Since we are interested in the benefits of adding storage at the margin, we assumed a value of 1 MW.
- $8{,}760$ is the number of hours in the study period and is used to convert the above values to an annual energy basis.
- $Energy_{stor}$ is the energy produced by the storage unit. Because storage is a net user of energy, this value is negative. For this study, we assumed an 80% round-trip efficiency and a 15% utilization, which on an annual basis equates to 328 MWh/yr consumed per unit of marginal storage added (i.e., per megawatt of storage added).

Finally, variable generation enabled and the fossil generation that could be avoided were obtained by solving the system of equations (Eq. (7)):

- Cap_{fossil} is the amount of the fossil capacity that can be avoided (either retired or new generation that would now longer be necessary). It has units of power (MW).
- Cap_{VG} is the amount for VG that must be built to satisfy the system of equations. It has units of power (MW).

Once the fossil generation avoided was calculated, it was straightforward to estimate the emissions avoided by simply applying a ReEDS-supplied emissions factor. Results were obtained for each of the 134 ReEDS balancing areas in the Mid-Case/Low Carbon scenario.