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How hydropower enhances the capacity value of renewables and energy efficiency

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A B S T R A C T

One of the ways that hydropower contributes to reducing carbon is by enhancing the ability of new resources, including renewables, to meet peak loads. An analysis concludes that the hydropower system can triple the capacity value for Columbia Gorge wind from initially low values and increase the capacity value of Southern Idaho solar by a factor of 10. Energy efficiency has the highest overall capacity value relative to average energy.

1. Introduction

As utilities and policy leaders explore and invest in strategies to reduce carbon and other emissions, it is important to recognize that not all power systems require the same solutions. The Northwest is unique in many ways, but the dominant role of hydropower enables one of the cleanest power systems in the world. There are at least three characteristics of hydropower that contribute to reducing emissions.

First, of course, is the fact that hydropower is essentially free of emissions.[1] Second, hydropower is also a relatively low-cost resource for providing balancing reserves, which are used to follow minute-to-minute fluctuations in loads and in wind and solar generation. Balancing reserves have been increasing recently due to the rise in wind and solar penetration. A thermal plant can provide a similar service but not as easily or as cheaply as a hydropower plant. For this reason, Northwest power operators generally hold balancing reserves on the hydropower system rather than on thermal plants, thus reducing carbon emissions.

The third clean energy characteristic is the storage value of hydropower. Energy associated with any resource, including wind, solar, and energy efficiency, can be effectively saved by reducing generation at a hydropower facility, leaving water in a reservoir for generation at a later time. This feature is associated with two sources of value: first, it can improve the fundamental economics of any resource, including renewables and energy efficiency, by effectively moving energy to higher-priced hours, and secondly, by potentially reducing the amount of additional peak generating capacity needed to maintain adequacy. It is this last function – the additional capacity gained by integration with the hydropower system, referred to as hydropower capacity storage − which is analyzed in this article.

Like a traditional battery, a hydropower system can save energy and generate it later. Unlike the case of traditional batteries, however, there are many other constraints on the operation of the hydropower system. Because dams are operated for multiple purposes, they need to fulfill obligations for flood control, irrigation, fish migration and spawning, transportation, and recreation. Taken together, these obligations limit the storage potential under certain conditions during certain times, days, seasons, and years. The essential point is that the hydropower system has considerable storage potential[2] at some times and at other times it is limited or nonexistent. Because of these many complicated operating rules, the best way to assess the storage value of the hydropower system is to run models that simulate its operation over thousands of possible future conditions.

2. Capacity

The Northwest Power and Conservation Council has adopted a specific adequacy standard for the Pacific Northwest, which requires a probability of 5% or less of having to curtail load at any time during a future year because of insufficient generating resources. This metric,

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[1] There is a possibility that the reservoirs behind dams may, in some instances, release greenhouse gases, in particular methane. These releases are likely to be relatively small in the Northwest especially compared to coal and gas plants. https://www.nwcouncil.org/media/7490995/p3.pdf.

[2] The Columbia River hydroelectric system has a considerable amount of storage capability in terms of energy but not so much relative to the average volume of water that flows down the river. The entire useable storage of the U.S. portion of the Columbia River hydroelectric system would generate (very rough estimate) about 2000 average-megawatts of energy, which is a considerable amount of energy. However, U.S. storage reservoirs can only hold about 15% of the annual average volume of water that flows through the system.

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commonly referred to as the annual loss of load probability (LOLP), is evaluated for the power supply five years into the future based on a model of the Northwest power system and published assumptions. The model simulates the operation of the power system 6160 times, with each simulation drawing from different combinations of future unknown factors – temperatures, river flows, wind generation and forced outages. Any simulation in which the load exceeds generation at least one time over the course of the year is counted as an adequacy miss. The annual LOLP is calculated by dividing the number of adequacy misses by the total number of simulations. For example, a result with 308 misses produces an LOLP of 5% (308/6160), which would be the minimum adequacy required by the standard.

This definition for adequacy allows power planners to calculate the capacity value of adding different resources to the existing power system. More precisely, the addition of any new resource should reduce the amount of additional capacity needed to meet the adequacy standard. For example, using a simulation model, the addition of 1000 MW (nameplate) of a wind resource is shown to generate 300 average megawatts (aMW) of energy and to reduce the amount of capacity required to meet the adequacy standard by 100 MW. In this case the addition of 1000 MW (nameplate) of wind reduces the capacity requirements by 100 MW, which means that the wind's integrated capacity value is 10% of its nameplate capacity. The integrated capacity value for wind is higher than the expected capacity contribution from wind generators without the interaction with hydropower system.

It should be noted that these capacity values are not universal and do not necessarily apply to any other power system or even the same system with a different resource mix. The capacity value is uniquely determined based on how a resource interacts with loads and other resources in the Northwest power system.[3]

A simple method for approximating capacity values can be illustrated graphically. Fig. 1 is based on a hypothetical model run to determine the capacity required to achieve a 5% LOLP. Suppose a future year's power supply is simulated stochastically 200 times and for each simulation the largest curtailment hour is graphed, sorted from highest (left) to lowest (right).[4] The largest curtailment hour has a shortage of 1500 MW and the smallest has a shortage of less than 100 MW. In total, there are 18 misses (out of 200) which represents a 9% loss of load probability. In order to achieve a 5% LOLP, the number of misses would have to be reduced to 10 (10/200 = 0.05). One way to achieve that target would be to add 500 MW of capacity to the system, thus eliminating misses 11 through 18 which are all 500 MW or less. Another way to state this conclusion is that this system requires 500 MW of capacity to achieve adequacy.

A more general approach replaces the number of misses on the horizontal axis with loss of load probability (LOLP) and the bar chart with a line as pictured in Fig. 2. Similar to Fig. 1, the figure shows that an increase of 500 MW of capacity is required to reduce the loss of load probability to 5%. Now suppose a new resource is added and the loss of load curve changes from A to B. With the new resource only 300 MW are required to achieve the adequacy standard, which means it has added 200 MW of effective capacity to the system. This provides a practical method for estimating the integrated capacity value of adding any resource to an existing power system. It is defined as *integrated* capacity because the resource is integrated into the power system, allowing the hydropower system to utilize whatever storage it has to avoid a loss of load.

[3] For more about the Northwest power system and how others calculate capacity values see Keane et al. (2010), NERC (2011), Milligan and Porter (2005), Rogers and Porter (2010), and the Seventh Power Plan.

[4] Each simulation is done with different combinations of temperature (demand), river flow, wind speeds, and forced outage conditions in the year being analyzed.

3. Hydropower system capacity storage

In order to measure the added capacity value provided by the hydropower system's storage, it is necessary to estimate the standalone capacity value of a new resource and compare that to the integrated capacity value. The *standalone* capacity is estimated by assuming that hydropower operations are not changed by the addition of the new resource. It can be estimated for non-dispatchable resources (wind, solar, and energy efficiency) by determining resource output during each of the loss of load events in Fig. 1 and reducing the loss of load accordingly. This is illustrated in Fig. 3.

This figure starts on the left with a ranking of peak hour curtailments similar to Fig. 1. The loss of load record changes when the wind resource happens to generate in the exact same hour as a loss of load event. Suppose a wind resource would have generated power during the 2nd, 5th, 8th, and 12th events represented by the shaded areas in the bars. Re-sorting the loss of load events from high to low produces a lower curve C, which is used to calculate the standalone capacity value of the additional resource without the benefit of the hydropower system.

The basic theory is summarized in Fig. 4. The base case (A) shows that 500 MW of capacity are required to achieve a loss of load probability of 5%. Adding a particular resource to the power system (B) reduces that need to 300 MW which means that the resource provides 200 MW of integrated capacity. Without the benefit of hydropower storage (C), the resource only adds 80 MW of standalone capacity (500–420). In summary, the resource adds 200 MW of capacity, of which 120 MW can be attributed to the effects of the storage of the hydropower system.

4. Results

The method described above was used to estimate both the integrated and standalone capacity values of several resources. Model simulations were performed for the Northwest power system and the results are reported in Table 1. The wind resource was located in the Columbia Gorge on the border of Washington and Oregon and the solar resource was a photovoltaic solar farm in Southern Idaho. Energy efficiency and a single-cycle natural gas plant are also included. Consistent with the theory, the integrated capacity is equal to the sum of standalone capacity and hydropower capacity storage.

There are several important results in this table, starting with the fact that the average energy produced from wind and solar resources is well below their nameplate capacities. This is because wind does not always blow and the sun doesn't always shine (in other words, their generation is limited by fuel supply). The annual energy production is about 30% of nameplate for wind and about 26% for solar.

For each resource the integrated capacity is greater than the standalone capacity and for some resources, much greater. Integrated capacity is 40% higher than the standalone capacity for energy efficiency (1184 MW compared to 713 MW), three times higher for wind (286 MW compared to 90 MW) and 10 times higher for solar (1157 MW compared to 109 MW). The interactions between these resources and the hydropower storage system adds significant capacity.

There is also a need to standardize the results so that different-sized resources can be compared. One way to do that is to calculate the ratio of integrated capacity to nameplate capacity for each resource. These ratios are presented in Table 2 for each resource except energy efficiency because it does not typically have a nameplate capacity.

As expected, investments in wind and solar provide capacity values, but in widely different proportions. Solar provides 0.39 MW of integrated capacity for each MW of nameplate capacity while wind only provides 0.10 MW of integrated capacity. In other words, each megawatt of solar adds four times as much net capacity to the system as a megawatt of wind. Because the standalone capacity is very similar for the two renewable resources, the difference in their integrated capa-

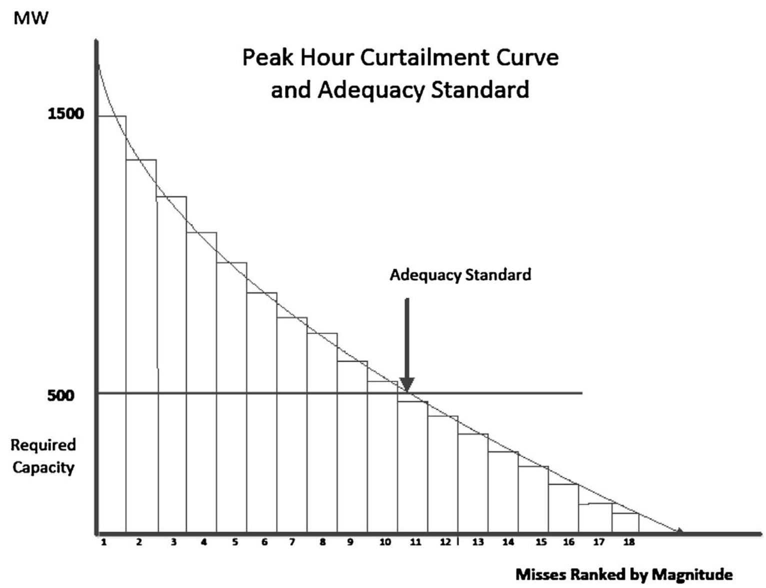

Fig. 1. Peak hour curtailment curve and adequacy standard.

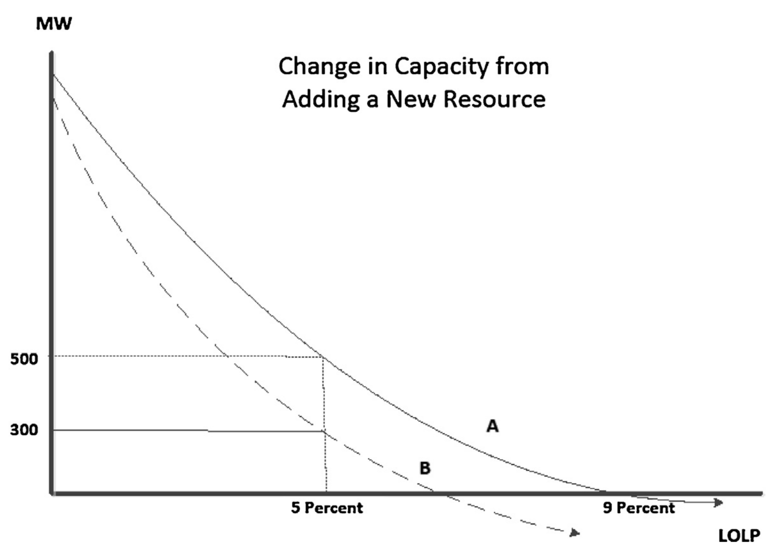

Fig. 2. Change in capacity from adding a new resource.

cities can be traced to the hydropower system. The hydropower capacity storage relative to nameplate capacity is 0.32 for solar compared to only 0.07 for wind.

Another way to compare capacity values is relative to average energy as presented in Table 3. This allows all resources to be compared, including energy efficiency.

Relative to average energy, the integrated capacity of efficiency is the highest of all resources. For each megawatt-hour of energy efficiency approximately two megawatts of capacity are provided. While the standalone capacity of efficiency is high, hydropower storage accounts for about 40% of its value. The high integrated capacity values of energy efficiency contribute to its overall cost effectiveness and is one of the reasons that it is the major resource in the Northwest Power and Conservation Council's 7th Power Plan.[5]

Southern Idaho solar provides the second-highest integrated capacity (1.48) when calculated relative to average energy, followed by natural gas (1.33) and Gorge wind (0.32). Most of the solar integrated capacity, 84%, is added by the hydropower system.

5. Discussion

Why does the hydropower system add so much additional capacity to Southern Idaho solar compared to Gorge wind? Both contribute comparable levels of standalone capacity, but once they are integrated with the hydropower system, solar displaces the need for about four times as much capacity as wind.

The hydropower system can only enhance the capacity value of a resource if it generates at a particular time, day, and season in which the hydropower system has available storage and can save water long enough to increase hydropower generation during a loss of load event. This requires a unique alignment between resource generation, hydropower operations, and loss of load events. Of particular importance is the availability of the power system to increase water storage prior to loss of load events.

Because storage opportunities are changing over time, it matters when a resource is generating power. The storage potential of the hydropower system is determined by matching the generating profile of a resource to the storage value of the hydropower system. It also

[5] As important as it is, capacity is only one source of value for energy efficiency. There is also the value associated with avoided energy generation, emissions reduction, reduced transmission and distribution costs, lower emissions, and risk reduction.

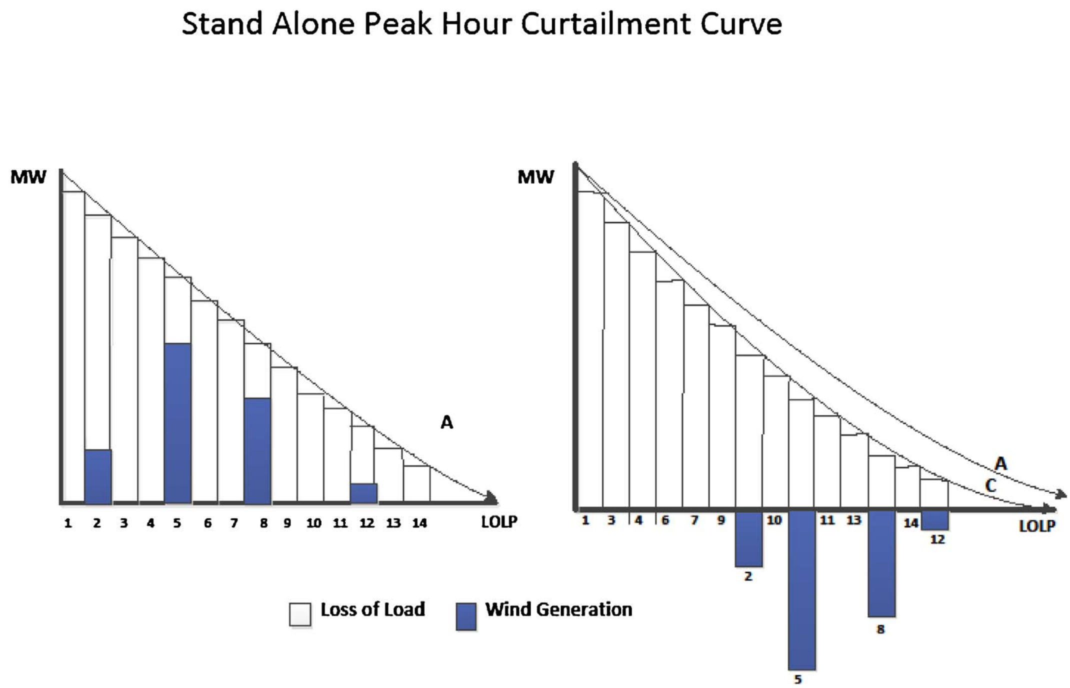

Fig. 3. Standalone peak hour curtailment curve.

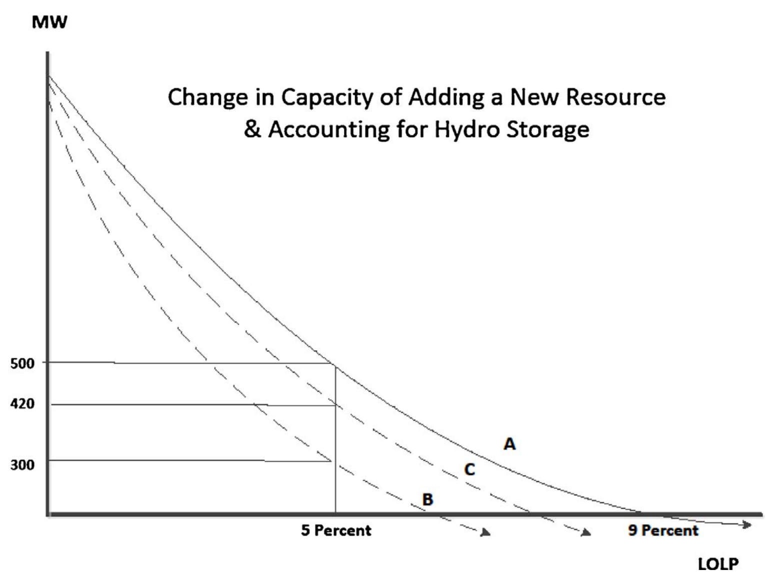

Fig. 4. Change in capacity from adding a new resource and accounting for hydro storage.

Table 1
Results of model simulations.

Resource	Nameplate Capacity	Average Energy (aMW)	Integrated Capacity (MW)	Standalone Capacity (MW)	Hydropower capacity storage (MW)
Wind	3000	900	286	90	196
Solar	3000	780	1157	109	968
Energy efficiency		600	1184	713	471
Natural gas[a]	4400	4180	5580	4400	1180

[a] Because natural gas is dispatchable, standalone capacity is simply equal to nameplate capacity.

Table 2
Ratio of integrated capacity to nameplate capacity.

Resource	Nameplate Capacity (MW)	Average Energy (aMW)	Integrated Capacity	Standalone Capacity	Hydropower storage capacity
			Relative to nameplate capacity		
Wind	3000	900	0.10	0.03	0.07
Solar	3000	780	0.39	0.04	0.32
Natural gas	4400	4180	1.27	1.00	0.27

matters if the power system has enough storage to accommodate renewable generation. A large amount of renewable generation at a single time may overwhelm the storage potential of the system.

There is evidence that Gorge wind is experiencing diminishing returns. The Northwest already has about 9000 MW of nameplate wind generation, much of it located in the Columbia Gorge. Adding an

Table 3
Capacity values relative to average energy.

Resource	Nameplate Capacity (MW)	Average Energy (aMW)	Integrated Capacity	Standalone Capacity	Hydropower capacity storage
			Relative to average energy		
Wind	3000	900	0.32	0.10	0.22
Solar	3000	780	1.48	0.14	1.24
Energy efficiency		600	1.97	1.19	0.78
Natural gas	4400	4180	1.33	1.05	0.28

additional 3000 MW of Columbia Gorge wind spreads the hydropower storage capacity benefits across a greater number of wind resources, thus reducing the incremental benefits of the last resources added. This result is probably unique to wind in the Columbia Gorge. Wind resources in Montana may contribute more capacity, both standalone and augmented by hydropower storage, because they have a very different output profile.

Solar does not experience the same diminishing returns, as there are only 235 MW of nameplate solar currently generating in the Northwest. Another important difference is that, because solar generates during the day, it is likely to overlap with system peaks and loss of load events. By itself, solar generation often does not have sufficient duration to reduce the loss of load over every hour of an event but with a little storage help from the hydropower system, it can make a significant difference.[6]

6. Qualifications and future work

This analysis only addresses the added capacity value of using hydropower storage in an integrated manner. Even if hydropower storage never addressed a loss of load event, it would be valuable because it can move energy from low-priced hours to high-priced hours. This is another function of the hydropower system that was modeled in the analysis but not separately reported.

Historically, hydropower system storage reduced the price differential between on- and off-peak prices, which limited the potential for traditional storage systems such as batteries and pumped storage. However, at some point, it appears that the sheer number of new renewable resources may exhaust the storage potential of the hydropower system, as we have seen with wind. The result may widen the on- and off-peak price differential and increase the potential for traditional storage. Since wind is also the primary renewable in the NW there may be more opportunity for a storage system compatible with a wind-generating profile. This hypothesis seems reasonable and could be tested when models are developed to add other storage systems to the resource mix.

The analysis assumes that hydropower storage is fully integrated with generation from renewables. This is often true because Bonneville Power Administration uses the federal hydropower system to integrate most of the renewables in the Northwest. But the integration of other renewables depends on markets which may not operate as smoothly as the analysis presumes.

Finally, it should be recognized that the results of this analysis depend on the metric and standard used to define adequacy in the Northwest, the 5% loss of load probability. A different standard could lead to a different quantitative result. This topic may be addressed in the future as the Northwest explores possible changes in the adequacy standard.

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[6] The hydroelectric system will operate in a way to "levelize" an expected shortfall. In other words, the expected shortage of generation is spread across the peak hours of the day in a uniform manner so that the shortfall can be alleviated by the addition of a single resource or a single flat energy purchase. This means that a typical "curtailment" event is spread out over the 16 peak hours of the day and obviously the sun does not shine 16hours of the day.