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The Impact of High Wind Power Penetration on Hydroelectric Unit Operations

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Abstract — **The Western Wind and Solar Integration Study (WWSIS) investigated the operational impacts of very high levels of variable generation penetration rates (up to 35% by energy) in the western United States. This work examines the impact of this large amount of wind penetration on hydroelectric unit operations. Changes in hydroelectric unit operating unit patterns are examined for an aggregation of all hydro generators. The cost impacts of maintaining hydro unit flexibility are assessed and compared for a number of different modes of system operation.**

***Index Terms*— power systems, wind power generation, hydroelectric power generation, stochastic systems**

I. Introduction

The growing amounts of variable generation (VG) being integrated into the electricity system are already starting to change system operations. As the penetration rates of these technologies increases further, significant changes in system operations are expected. The Western Wind and Solar Integration Study [1] (WWSIS) investigated the operational impacts of very high levels of VG penetration rates (up to 35% by energy) in the western interconnection of the United States. In the largest scenarios, 30% of energy in the WestConnect footprint was supplied by wind power, with an additional 5% split between concentrating solar thermal (CSP) and solar photovoltaic (PV) generators. While the WestConnect area was the focus of the study, the entire WECC area was modeled due to the strong interactions between the two areas.

WWSIS studied system operations in the year 2017, based on expected system loads, generation unit retirements and expansions and transmission build-out. While such high levels of VG penetration are not expected by 2017, the choice of this year allows for reasonable assumptions about the rest of the system, and most importantly, the transmission grid, to be made without requiring long-term forecasting of system changes. To capture the operational effects of this influx of VG, a transmission-constrained hourly production cost model (GE MAPS) was used in modeling the WECC area. Because there can be large differences in operations on an inter-annual basis, the same year was modeled three times, utilizing time-synchronized load, wind, and solar data from the years 2004, 2005, and 2006. Because there are not currently as many wind and solar sites in WECC as were modeled in the study, wind and solar power output time-series data had to be simulated using a numerical weather prediction (NWP) model [2]. Though the goal of the study was to model a system close to current system operations, some simplifying assumptions were made. The most important of these was using only five regional balancing areas in the study, instead of the 37 that existed in WECC at the start of the study. Balancing area consolidation has long been a trend in the United States electricity system, and has also been proposed as a change in system operations that would be helpful in integrating additional amounts of VG; though this degree of consolidation is not anticipated in the near future. The transmission system was reduced to 20 transmission zones with only inter-zonal lines modeled.

In this work, we examine how the high wind penetration levels modeled in the WWSIS impact hydroelectric unit operations. Hydroelectric power is often seen as the perfect complement to wind power because hydro units are quick-starting and, therefore, can balance variations in wind power output. However, the reality is not quite as simple due to non-power constraints on hydro units. Since hydroelectric units often have water use constraints, they may be required or prevented from operating at certain times to maintain reservoir levels, or required to generate in order to avoid spilling.

Belanger and Gagnon examined the effects of using a hydroelectric plant as a backup system to balance the variability of a single wind plant [3]. While they chose a system with large amounts of hydro power generation, specifically Quebec, Canada, they did not look at the system-wide effects on all hydro generators, and instead chose to focus on a single hydro plant. A number of other studies have also examined combined wind-hydro systems, usually on small island systems where close to one–to-one backup of wind power is necessary because of the paucity of other generators [4, 5]. However, one must be careful about applying the results generated with this approach to larger systems because wind power does not require one-to-one backup in larger systems. Instead, balancing the reduced variability of a number of different wind plants together is a more efficient approach [6]. One study that considers a larger system is Benitez et al. [7] which looked at using an aggregation of hydropower plants to balance wind power in two high wind scenarios. Specific concerns addressed were the need for new thermal generation, the costs of wind integration, and the costs of reducing CO_2 emissions.

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II. WWSIS METHODS AND DATA

In this section, we describe some of the important details of the methods and data utilized in the study. Section II-A contains information on the various scenarios run in the WWSIS, in terms of wind penetration rates and wind plant locations. Section II-B provides details on how the hydroelectric units were modeled within the production cost simulation model.

A. Scenarios

The wind resources available in the Western Interconnection can vary widely in quality from location to location. The choice of where to site the proposed wind plants that would combine to meet the study's renewable penetration goals is influenced by many factors. For this reason, three different siting scenarios were devised: the In-Area, Mega Project and Local Priority scenarios. The In-Area scenario forced the areas within WestConnect to fulfill their renewable goals with resources located in their area of responsibility, and will be the focus of our analysis of the effect of high wind power penetration on hydro generator operations.

Though a goal of the WWSIS was to examine the impact of VG penetration rates above 30% on electricity system operations, the changes that would occur in the system at lower penetration rates on the trajectory to 30% are also important. For this reason, four penetration rate scenarios were included in the study. The lowest penetration rate case examined the impact of 10% wind energy and 1% solar energy in both the WestConnect area and the rest of WECC. There were two 20% cases created. One examined 20% wind energy and 3% solar energy penetration in both WestConnect and WECC as a whole. The other included only 10% wind energy and 1% solar energy in the rest of WECC, while keeping WestConnect at 20% and 3% for wind and solar energy penetration respectively. The final case examined penetration rates of 30% wind energy and 5% solar energy for WestConnect, with the balance of WECC only having a 20%/3% split. In our analysis of the impacts on hydro generators, we will continually use the different penetration cases to examine the impact of increasing VG penetration.

B. Hydroelectric Modeling

Unlike the wind and solar data used in the WWSIS, the hydroelectric modeling does not use time series data specific to the climate patterns of 2004-2006. Since hydro units are dispatchable, modeling their operation solely on a historical dataset would have increased the perceived integration cost by neglecting the hydro unit flexibility. Instead, each plant was assigned monthly energy and plant capacity limits based on 11 year averages of these generator specific variables. This allowed the production cost model to dispatch the hydro resources, subject to their monthly constraints. One limitation of this approach is that it always assumes that the full hydro generator nameplate capacity is available, regardless of current reservoir levels. By not explicitly modeling the reservoir levels at all of the hydro units, some of the water usage and non-power constraints and requirements found in actual unit operation are neglected. Some of these issues include: recreational water levels, irrigation, flood control, and dissolved gas levels. While they may greatly affect hydro generator production levels, the above named issues are also very unit- and situation-specific, making a full accounting of all possible constraints in all contingencies beyond the scope of a WECC-wide study such as WWSIS.

III. RESULTS

Hydroelectric units can behave quite differently than thermal units in normal power system operations, and so case studies were performed to examine how the hydroelectric units might operate in a high VG scenario. Hydroelectric units have the advantage of being quick-start, however, they also have constraints on their generation based on maintaining reservoir levels within appropriate bounds. Additional analysis was conducted on the impact of using hydro generation as flat capacity instead of flexible generation on total system costs. Since the high levels of variable generation modeled require greater system flexibility, hydro power becomes a very valuable resource due to its flexibility; as evidenced by the higher costs associated with flat hydro production when compared with flexible production.

A. Aggregate Hydroelectric Generation

Since some of the modeling assumptions in the WWSIS study differ from current system operations, even in the no wind case, the operation of individual hydroelectric units should not be expected to perfectly mimic current operational practices. However, this does not mean that changes in operational patterns over the entire class of hydro units cannot be discerned. For example, as seen in Figure 2, the hourly output levels do change slightly as the wind penetration level increases. Whereas, the total monthly energy for hydro units remains constant and so the daily output may shift slightly from the day to the night, or vice versa, depending on the corresponding wind output. This difference can be quite significant. In Figure 1, on April 14th the difference between the no wind hydro output and 30% case is as large as 15 GW of power at one point.

While the higher wind penetration rates can cause the hydroelectric units to operate quite differently at specific time points, overall changes in operational patterns are more important. One way to see the large scale differences in operation is by examining a generation duration curve for all hydro units over the course of a year. Figure 2 shows these curves for the no wind, 10%, 20%, and 30% in footprint scenarios. As may be observed, the curves are very similar for all four cases, showing that while the combined hydro production may be quite different at certain moments in time, the general pattern of usage is not significantly changed.

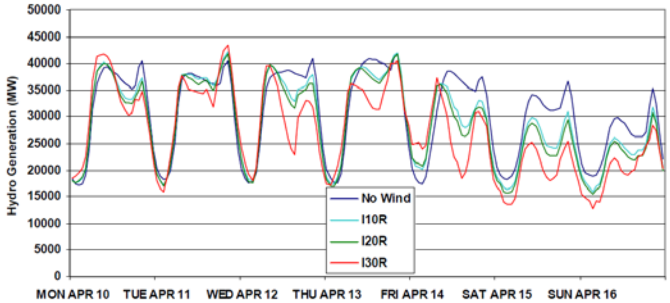

Figure 1. Total hydro generation in the different In-Area wind penetration scenarios for the week of April 10th.

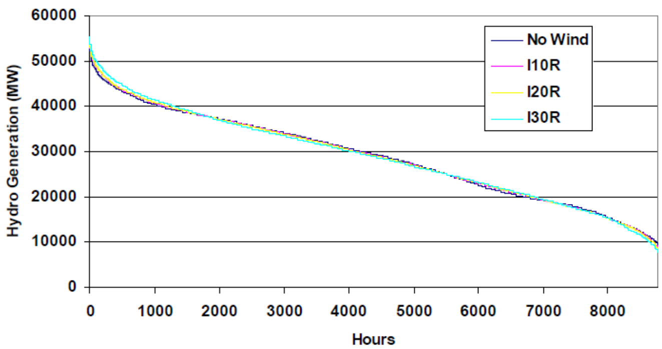

Figure 2. Annual generation duration curve for all hydro units in WECC in the different In-Area wind penetration scenarios.

One place where the high wind power penetration rates make a significant impact is on the spot prices that occur during hydropower operation. As may be seen in Figure 6, there are noticeably lower spot prices across the entire year in the high wind penetration rates than in the no wind case. At the end of the spectrum with the lowest prices, the 30% wind cases have spot prices that are approximately $50/MWh lower than in the no wind case. These changes are to be expected due to the essentially zero marginal operating costs of wind plants, however, the overall loss in revenue for hydro generators implied by the lower spot prices is very important.

Finally, we examined an operational decision that can have a large effect on total system operating costs; whether to schedule hydro units based on total system load or net system load. We define net load in this case as the load remaining after subtracting expected wind generation from the load. Scheduling hydro units based only on load limits the utilization of their flexibility for balancing wind variability. The additional operating costs to the system for the 10%, 20%, and 30% wind penetration scenarios may be seen in Figure 4. The cost of this lost flexibility is relatively modest in the two lower wind penetration cases, but increases significantly in the 30% wind case.

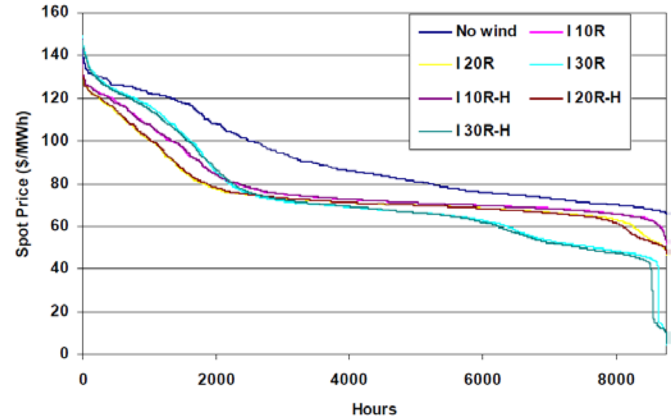

Figure 3. Spot price duration curve of hydro unit operation for the different In-Area wind penetration scenarios.

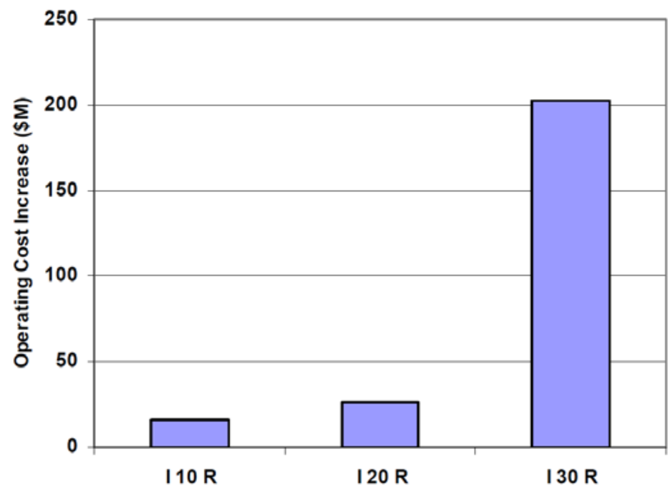

Figure 4. Operating cost increases for dispatching hydro based on only load versus net load for the different In-Area wind penetration scenarios.

B. Flat Block Hydro

The flexibility of hydroelectric generators to start and ramp quickly is expected to be an important attribute with increasing VG penetration. To help assess the value of hydropower being able to balance system variability, a comparison was performed between two modes of hydro operation: allowing hydro units to be dispatched and grouping all hydropower together as a flat block. In the flat block case, the hydro units were restricted to producing at a fixed rate during all times of the day, with the production level varying from month to month, based on the seasonal monthly production averages.

The total system operating costs for a variety of wind penetration scenarios, both with and without flat hydro blocks, are displayed in Figure 5. Immediately noticeable are the decreasing total system operating costs with higher penetrations of wind energy due to the zero marginal cost of wind power. Also immediately apparent are the higher costs in every scenario when a flat hydro block is used instead of allowing hydro to be dispatched.

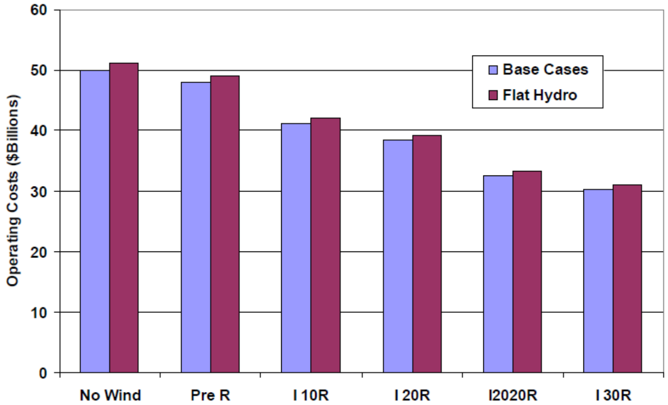

Figure 5. Total system operating cost changes due to flat block hydro operation for the different In-Area wind scenarios.

Figure 6 provides a closer look at the differences in cost between the dispatchable and flat hydro cases. An interesting result is that the incremental decreases in operating cost between the two forms of hydro operation is lower for each of the wind penetration cases than for the no wind case. However, one must also remember that the total operating costs are lower in the high wind penetration scenarios. Therefore, the percentage decrease in total operating costs are fairly similar for all the cases, with the highest wind penetration rates having slightly higher percentage cost increases when using the flat block operation.

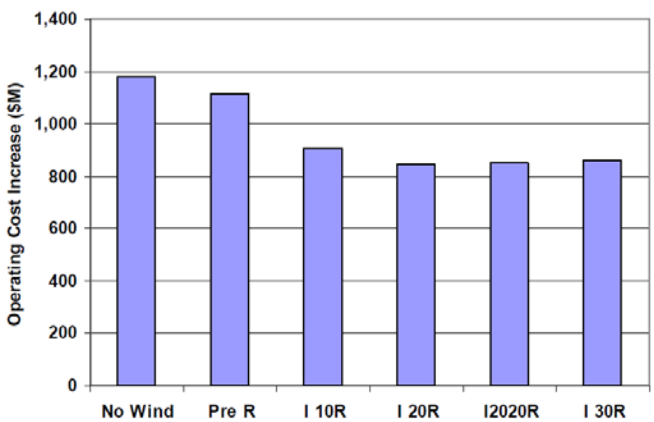

Figure 6. Incremental operating cost increase due to flat block hydro production in the various In-Area penetration rate scenarios.

Another way to assess the impact of the flat block hydro operating policy is through the examination of the spot price duration curve. Figure 7 shows this curve for the no wind and 30% penetration scenarios for both hydro operation modes. The flat block operation of hydro units has an amplifying effect in the no wind case. During times of high spot prices, the flat block creates even higher prices by not being available as a cheap dispatch solution. In the lower price cases, which most often occur during times of low system load, the flat hydro block further reduces system prices. In the 30% wind scenario, the dispatchable and flat block cases are very similar for most of the year. It is only during the lowest cost hours that the flat block case further reduces the spot price.

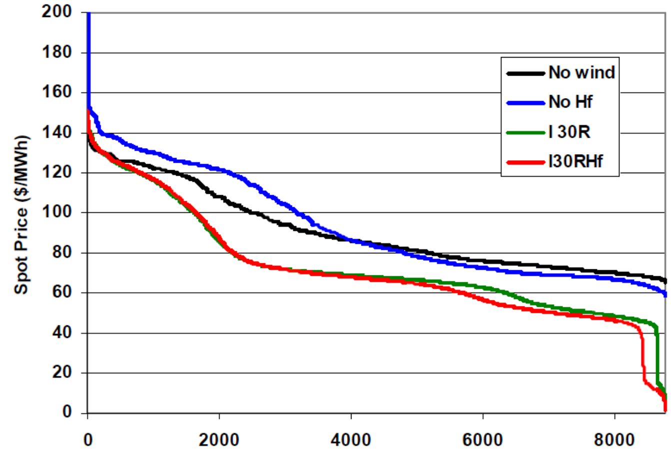

Figure 7. Spot price impact of flat block hydro in the no wind and 30% wind penetration In-Area scenarios.

IV. Conclusion

In this work, we have examined the impact that high wind power penetration rates will have on hydroelectric unit operations in the western United States. Though hydroelectric generators' flexibility is often seen as the perfect complement to variable and uncertain wind power, the physical flexibility of the generators is often reduced by non-power constraints. Another important result is the establishment of the significant total system cost increases that arise from not utilizing this flexibility, as was determined by examining flat-block hydro operation. In order to more accurately establish the effects of high wind penetrations on hydro system operations, the non-power constraints must be modeled on a unit-by-unit basis. In summary, the flexibility of hydro units can be an important factor in reducing total system costs, so long as that flexibility is available to the system.

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