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The Impact of High Wind Power Penetrations on Hydroelectric Unit Operations in the WWSIS

Bri-Mathias Hodge, Debra Lew, and Michael Milligan

***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 report examines the impact of this large amount of wind penetration on hydroelectric unit operations. Changes in hydroelectric unit operating patterns are examined both for an aggregation of all hydro generators and for select individual plants. 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), chiefly wind and solar power, being integrated into the electricity system are already starting to change system operations. As the penetration rates of these technologies increase even more, 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 a portion of the western interconnection of the United States. In the most extreme 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 U.S. portion of WECC was modeled due to the interconnected nature. The details of the WestConnect and WECC boundaries can be seen in Figure 1.

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. In order 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 system 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 [3], 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 interfaces modeled. It was assumed that there were no transmission limits for transfers within each of the transmission zones. Additionally, the $9.50/MBTU price for natural gas used in the study means that new VG primarily displaces gas-fired generators, with the consequence that coal plants accommodate much of the variability of wind and solar production.

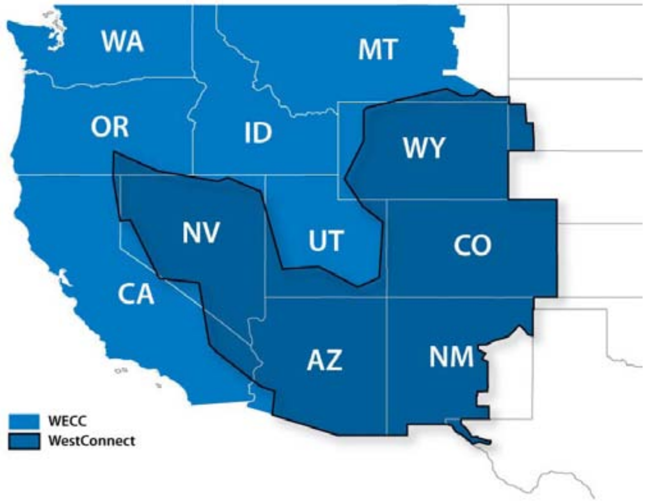

Figure 1 − Map of the WWSIS footprint including WestConnect and WECC boundaries [1].

In this report, we examine how the high wind penetration levels modeled in WWSIS impact hydroelectric unit operations. Hydroelectric power is often seen as the perfect complement to wind power because hydro units are quick-starting with high ramping rates 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 produce in order to avoid spilling that would cause exceeding environmental limits on dissolved gases.

Belanger and Gagnon examined the effects of using a hydroelectric plant as a backup system to balance the variability of a single wind plant [4]. 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. Unsurprisingly, they found that the output of the hydroelectric plant was significantly different when used exclusively to balance the output of a single wind plant, and that this had a significant impact on river levels at different times of the year. 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 [5, 6]. However, one must be careful about extrapolating these results 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 with the variability of load is a more efficient approach [7]. One study that considers a larger system is Benitez et al. [8]. This study looked at using an aggregation of a number of hydropower plants to balance wind power in two different high wind scenarios for Alberta, Canada. Specific concerns addressed were the need for new thermal generation, the costs of wind integration, and the costs of reducing CO_2 emissions. Bueno and Carta [6] is also significant because it suggests the use of pumped hydro storage as a means of dealing with wind power variability, a topic of interest in a number of other studies [8-10].

The remainder of the report is organized as follows. In Section II, the methods and data used in this study are described in detail. Section III contains the results of WWSIS, specifically with regard to the effects of high wind power penetration on hydroelectric unit operations. Conclusions are then drawn and future areas for examination outlined in Section IV.

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 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 such as: the quality of local resources, local siting and political factors, and transmission capacity availability and cost. 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 local resources located in their area of responsibility. The Mega Project scenario selected the best quality resources within the total footprint, and then built transmission between the areas so that the whole footprint met its renewable goal. The Local Priority scenario is a combination of the other two scenarios that mixes some inter-area transmission building with a focus on providing substantial amounts of generation locally. One of the more surprising results of the WWSIS was that the scenarios chosen had relatively minor impacts on the system at the operational level. This result is believed to be heavily influenced by the choice of using only five balancing areas, and would likely change if all of the current balancing areas were modeled individually. For this reason, we will focus mainly on the In-Area scenario in our analysis of the effect of high wind power penetration on hydro generator operations.

Though a goal of 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 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 Generation 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 and can be used to balance wind power variability, 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 variable generation 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. Since some hydro units have historically been used as load following units, with changes in production based on changes in forecast demand, case studies were performed to examine the difference in operations when the units were scheduled both before and after renewables. Additional analysis was conducted on the impact of using hydro generation as flat capacity (in order to fulfill reservoir water use constraints) instead of flexible generation on total system costs. Since the high levels of VG modeled require greater system flexibility, hydro power becomes a very valuable resource, 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 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. When examining the output patterns of all hydro units in the different penetration rate scenarios, changes in hydro operation start to become apparent. For example, as seen in Figure 2, the hourly output levels do change slightly as the wind penetration level increases. However, 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 2, 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. During times of lower wind power output, such as the month of July shown in Figure 3, the daily aggregate hydropower output patterns may still differ. However, the differences between the no wind case and high wind penetration scenarios are less significant than during times of high wind power output.

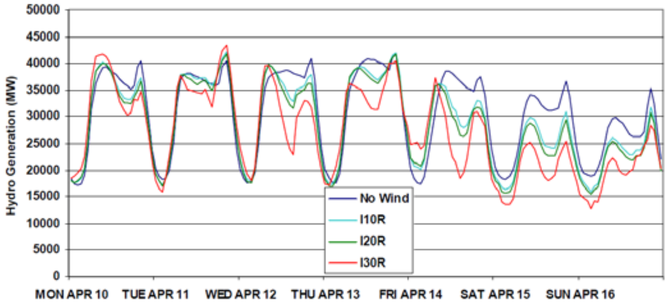

Figure 2 − Total hydro generation in the different In-Area wind penetration scenarios for the week of April 10th.

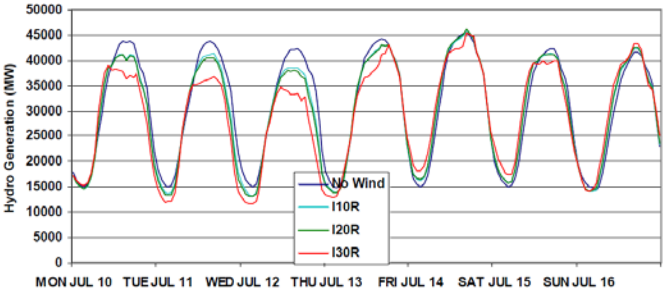

Figure 3 − Total hydro generation in the different In-Area wind penetration scenarios for the week of July 10th.

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 4 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.

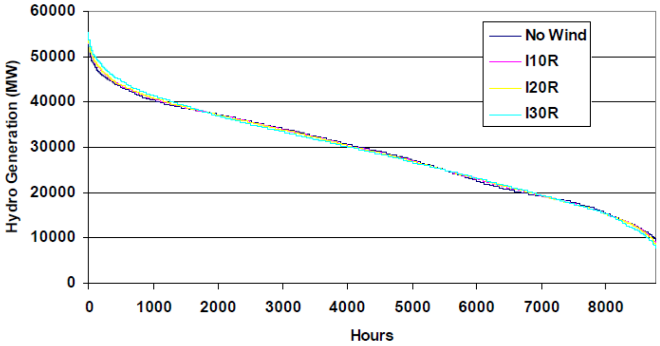

Figure 4 − Annual generation duration curve for all hydro units in WECC in the different In-Area wind penetration scenarios.

Another way of examining the patterns of change from high wind penetration is by viewing the hourly changes in production over the course of the year. Figure 5 shows the hourly change in production from all generators over the course of the year in a generation change duration curve. Once again, we can see that the duration curves are fairly similar for the three cases. In this case, we do observe a small difference in the 30% wind case at the relatively larger negative generation changes, with the high wind case actually producing slightly smaller negative changes in generation than the other cases.

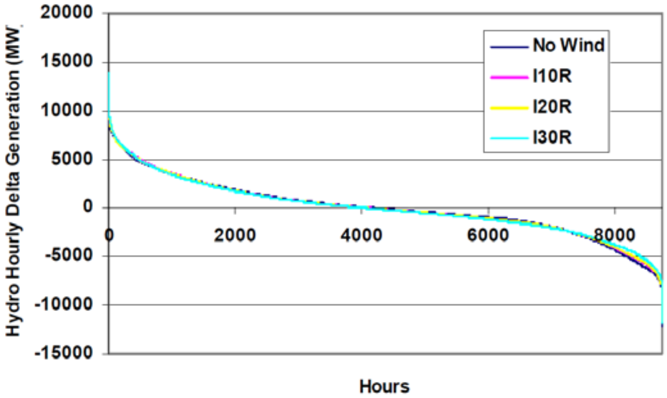

Figure 5 − Annual hydro hourly delta duration curve for all WECC hydro generation in the different In-Area wind penetration scenarios.

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.

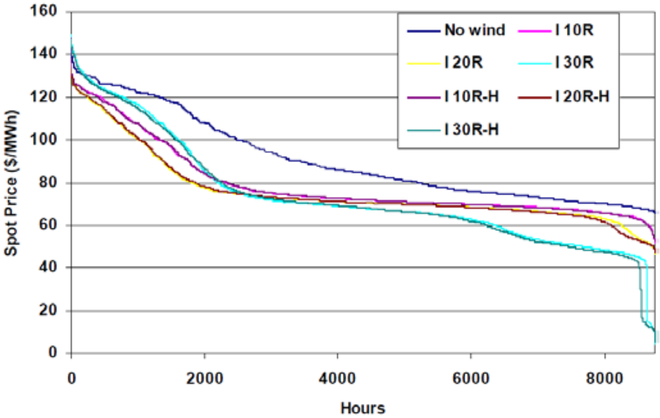

Figure 6 − Spot price duration curve of hydro unit operation for the different In-Area wind penetration scenarios.

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 defined net load in this case as the load remaining after subtracting expected wind and solar 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 7. The cost of this lost flexibility is relatively modest in the two lower wind penetration cases, but increases significantly in the 30% wind case.

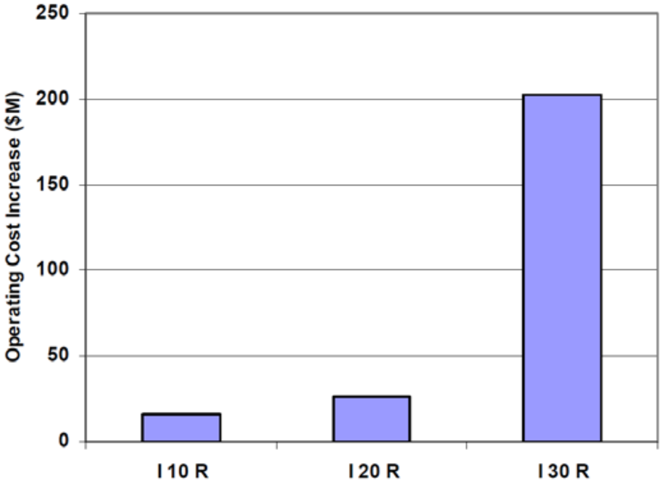

Figure 7 − Operating cost increases for dispatching hydro based on only load versus net load for the different In-Area wind penetration scenarios.

B. *Individual Units*

As previously described, the assumptions made in the WWSIS dictate that the usage patterns of individual hydroelectric plants seen in the study will differ from those seen in current usage. Nevertheless, examining the usage patterns of the individual units can offer interesting insights, such as how hydropower plants might operate with fewer water usage constraints or in a system with larger balancing areas. Eight individual hydro generators operated by the U.S. Bureau of Reclamation and located in the WestConnect footprint were chosen for further study. The particular units chosen are shown in Table I.

TABLE I

HYDRO FACILITIES IN WESTCONNECT SELECTED FOR FURTHER STUDY

Plant Name	Nameplate Capacity
Hoover Dam	2,074 MW
Glen Canyon Dam	1,296 MW
Davis Dam	240 MW
Morrow Point Dam	173.2 MW
Blue Mesa Dam	86.4 MW
Mt. Elbert Pumped Storage Facility	200 MW
Parker Dam	120 MW
Crystal Dam	32 MW

Once again, we will use an output duration curve, this time to assess how the output of the selected hydro plants in the simulation compares to actual system operations. The aggregated output from the seven selected sites, not including the pumped storage facility, is compared for different wind penetration and siting scenarios against actual plant output from 2006 in Figure 8. It is important to keep in mind that 10-year monthly average hydro plant output was used in the simulation, instead of actual 2006 output. Therefore, the total energy production in the simulation case is roughly 20% higher than in the actual 2006 output, as 2006 was a low output year for hydro. Even recognizing this fact, a clear difference in usage patterns is still noticeable. The simulated scenarios have a much wider range of usage than the actual output, with a higher instantaneous generation level and much more time at minimum generation levels as well. This implies that the simulation is cycling the hydro resources from high to low output more often than is seen in actual usage patterns. This is believed to be largely a result of the smaller number of balancing areas, freeing the hydro units from serving primarily as local balancing units.

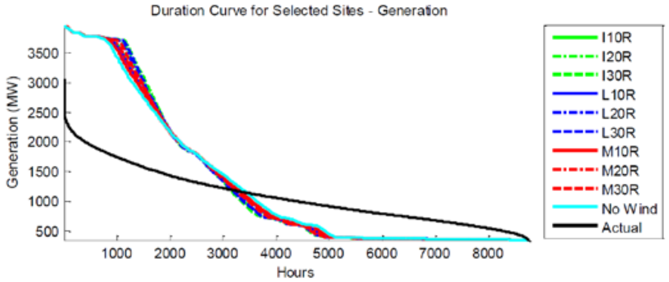

Figure 8 − Duration curve of aggregated output from the selected sites versus actual 2006 output for different wind penetration scenarios.

To examine the impact of the hydro generator operating assumptions on system operations, another simulation run was performed where the nameplate capacity and monthly energy levels of the selected hydro units were de-rated to 2006 levels, based on the historical reservoir levels. As may be seen in Figure 9, the de-rating produces a duration curve for the sites that more closely resembles actual operations. However, the generator's output still spends significantly more time in the higher and lower operating regions than is observed in historical operations.

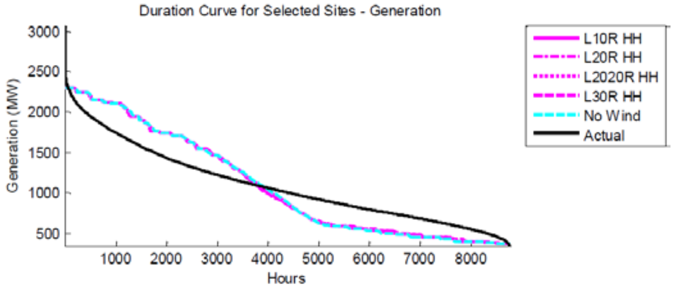

Figure 9 − Duration curve of aggregated output from the selected sites versus actual 2006 output for different wind penetration scenarios after adjusted the maximum capacity and monthly energy levels based on historical data.

The differences in unit operation patterns can best be observed by examining an individual unit at a shorter timescale. Figure 10 shows the hourly dispatch for the Hoover dam over a one week period in July for actual unit operations, a no wind case, and a 20% penetration scenario. Both of the simulated cases display much more consistent unit behavior than the historical data. The simulated cases switch between high output and minimum output in a diurnal step-function pattern. The historical data, on the other hand, shows much greater variation in output, suggesting that it is being used for load following, along with its primary purpose of water flow control. This same phenomenon can be observed only during some of the days shown in Figure 11, which is based on an April week with higher wind output. The fact that the simulation does use the same unit for load following, albeit less often than historical operations would suggest, is likely the result of the lesser number of balancing hours used in the simulation than in actual operations. This allows the hydro generator to serve as a baseload unit more frequently.

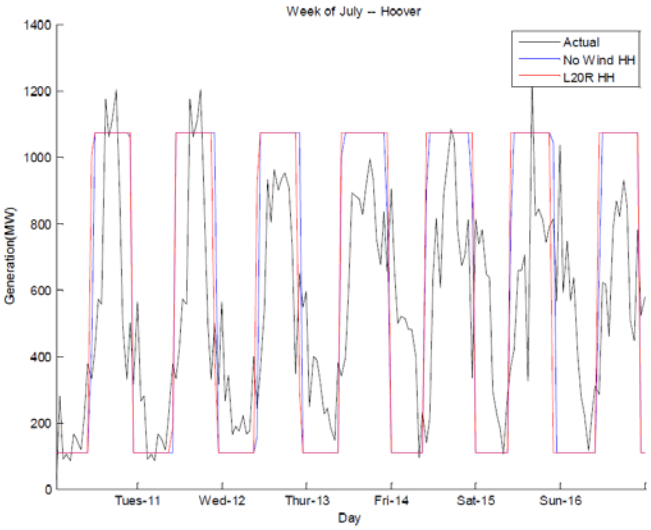

Figure 10 – Hourly dispatch from Hoover Dam during a one-week period in July 2006 for actual operations, a no wind case, and a 20% penetration scenario.

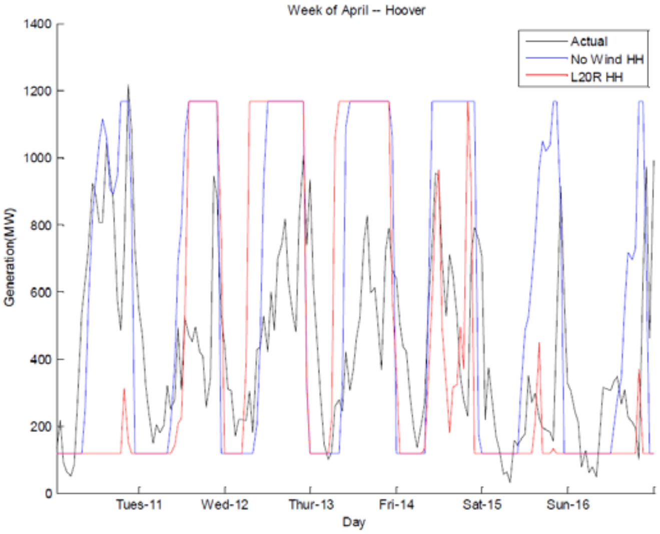

Figure 11 – Hourly dispatch from Hoover Dam during a one-week period in April 2006 for actual operations, a no wind case and a 20% wind penetration scenario.

C. Flat Block Hydro

The flexibility of hydroelectric generators to start and ramp quickly is expected to be an important attribute with increasing VG penetration. In order 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. Figure 12 shows an example of the difference in the two types of hydro operation at the Hoover Dam.

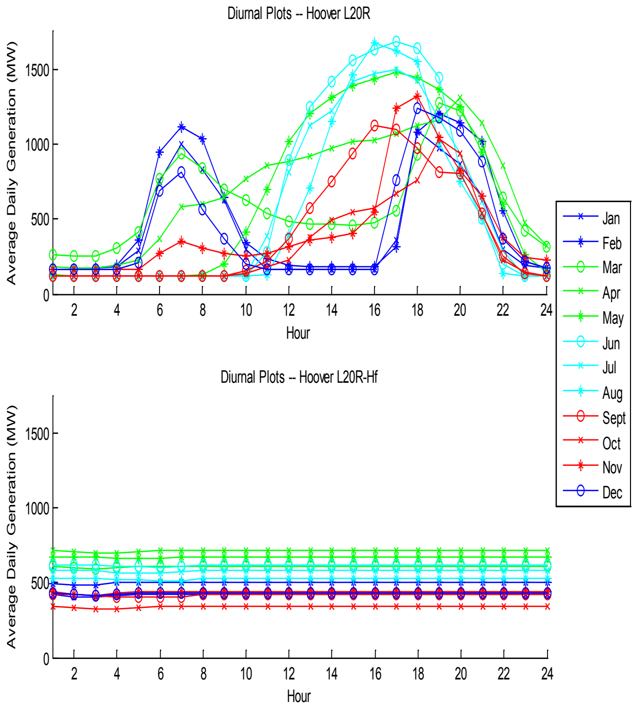

Figure 12 − Average production at Hoover Dam by hour of day for each month in the hydro dispatching and flat block cases [11].

The total system operating costs for a variety of wind penetration scenarios, both with and without flat hydro blocks, are displayed in Figure 13. 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.

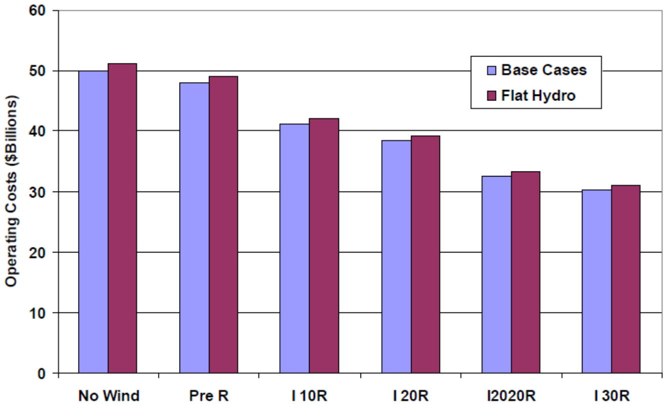

Figure 13 − Total system operating cost changes due to flat block hydro operation for the different In-Area wind scenarios.

Figure 14 provides a closer look at the differences in cost between the dispatchable and flat hydro cases. An interesting result is that the absolute increase 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 relative decrease in total operating costs are fairly similar for all the cases, with the highest wind penetration rates having slightly higher cost increases when using the flat block operation.

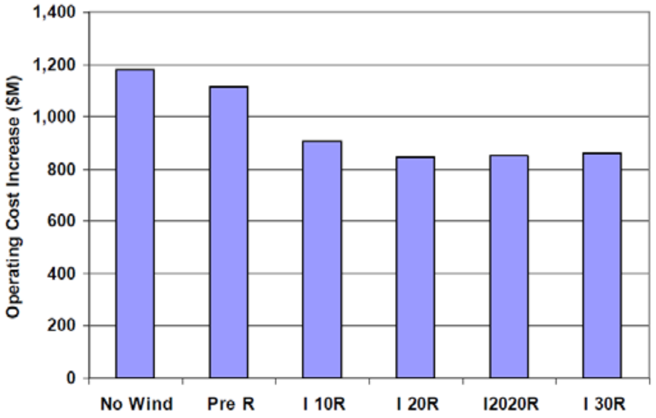

Figure 14 − Incremental operating cost increase due to flat block hydro production in the various In-Area penetration rate scenarios.

Another way to assess the impact of the flat block hydro operating policy is through the examination of the spot price duration curve. Figure 11 shows this curve for the no wind and 30% penetration scenario 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.

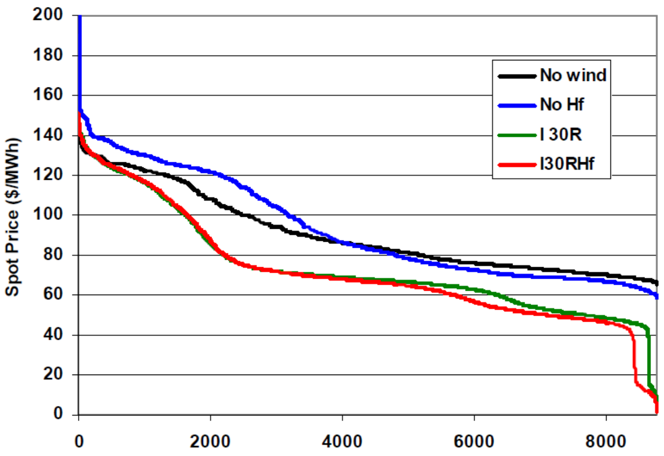

Figure 15 − Spot price impact of flat block hydro in the no wind and 30% wind penetration In-Area scenarios.

IV. CONCLUSION

In this report, we have examined the impact that high wind power penetration rates will have on hydroelectric unit operations in the western United States. Since hydroelectric generator's flexibility is often seen as the perfect complement to variable and uncertain wind and solar power, it is important to schedule the hydro generation based on expected net load instead of load alone, to better utilize this flexibility. 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. It is important to note that the operation of hydro units is often strongly influenced by non-power considerations. To more accurately establish the effects of high wind penetrations on hydro system operations, these non-power constraints must be modeled on a unit-by-unit basis, a difficult task due to modeling and data availability limitations. In summary, the flexibility of hydro units can be an important factor in reducing total system costs, so long as that flexibility is made available to the system.

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