Reserve Requirement Impacts of Large-Scale Integration of Wind, Solar, and Ocean Wave Power Generation

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Abstract—Many sources of renewable energy, including solar, wind, and ocean wave, offer significant advantages such as no fuel costs and no emissions from generation. However, in most cases these renewable power sources are variable and non-dispatchable. The utility grid is already able to accommodate the variability of the load and some additional variability introduced by sources such as wind. However, at high penetration levels, the variability of renewable power sources can severely impact the utility reserve requirements. This paper presents an analysis of the interaction between the variability characteristics of the utility load, wind power generation, solar power generation, and ocean wave power generation. The results show that a diversified variable renewable energy mix can reduce the utility reserve requirement and help reduce the effects of variability.

Index Terms—Power system stability, wind power generation, solar power generation, marine technology, power systems, load forecasting, load modeling, reserve requirements.

I. NOMENCLATURE

BPA: Bonneville Power Administration
BAA: Balancing Authority Area

II. INTRODUCTION

Many balancing areas within the United States are faced with a rapidly expanding wind power resource. For example, it is predicted that as much as an additional 5,000 MW of new wind power could come online within the next five years in the Pacific Northwest [1].

At low penetration levels, the variable output of wind power plants is easily absorbed within the variability of the load [2]. However, as the penetration level increases, the added variability of the wind resource can cause greater ramp-rates, greater inter-hour variability, and greater scheduling error. This ultimately increases the amount of generation the system operators must hold in reserve (i.e., the reserve requirement) to accommodate the unplanned excursions in wind generation.

Wind power is now a very mature and established renewable resource throughout the world. However, other renewable power sources such as solar (PV or concentrating/thermal) and ocean wave energy also have significant potential. Solar has recently been the beneficiary of a number of large-scale initiatives (e.g., California Solar Initiative), and there is currently a good amount of industrial activity regarding wave energy, particularly for development in the Pacific Northwest of the U.S.

A. Wind, Solar, and Wave Generation Characteristics

Each of these renewable power sources can be described by three major characteristics.

1. Variable. The output power of a large-scale wind, solar, or wave power plant varies over time. The vast majority of the time, the variability from one minute to the next is very small, and even the hourly variation is usually small. However, on occasion the output of a large plant, as high as several hundred MW, may go from full output to low production or vice versa over several hours [3].

2. Non-dispatchable. As implemented now, the system operator has very limited control of the output of large-scale renewable generation. In general, the operator must deal with whatever the renewable generation outputs are in much the same manner as dealing with the load. Therefore it is common in the analysis of the impact of renewable power generation to subtract its contribution from the load: renewable power generation appears as a negative load.

3. Energy source. Due to the non-dispatchable nature of wind, solar, or wave, they generally have a relatively low capacity credit. That is, they do not make a significant contribution to the power requirements of the grid for planning purposes. However, each Joule of energy converted by a renewable source is one Joule saved for “traditional” generation, such as coal. Therefore, renewable energy sources can make a significant impact on the energy requirements of the grid.

B. Reserve Requirements

The variable, non-dispatchable nature of wind, wave, and solar has a significant impact on the utility reserve requirements [4]. Analyzing the effect of these renewable energy sources on the reserve requirements provides a meaningful and concrete method of characterizing the variability of a given renewable energy source, including its short and long-term correlation with the load.
C. Research Objective

A number of research groups have analyzed the impact of large-scale wind integration on utility operation, including reserve requirements [5], [6]. Some research has also been extended to include large-scale solar [7]. The research presented in this paper analyzes the reserve requirements for the Pacific Northwest of the United States including wind, solar, and ocean wave energy. The hypothesis is that the temporal and spatial variability characteristics of wind, wave, and solar will allow a greater combined penetration rate than using only one predominate type of renewable power source (e.g., wind).

The reserve requirements for six scenarios are compared.
1. No renewable energy (only load).
2. 15% wind power penetration.
3. 10% wind and 5% solar penetration.
4. 10% wind and 5% wave penetration.
5. 10% wind, 2.5% solar, and 2.5% wave penetration.
6. 5% wind, 5% solar, and 5% wave penetration.

Penetration is defined in this research as the ratio of the peak load within the year to the peak generation within the year.

If the hypothesis holds, scenarios in which there is a greater diversity of renewable power will have lower reserve requirements than for the scenario with only 15% wind penetration.

III. DATA SOURCES

The data used in this study came from a variety of both real and simulated sources. The area of study is within the Pacific Northwest, mostly within or near the Bonneville Power Administration Balancing Authority Area. Wind and load data for the BPA BAA are both freely available directly from BPA [8]. The solar and ocean wave data were generated. All data, and the analysis, covers the calendar year 2008 starting Jan. 1. The sample time for the load, wind, solar, and wave power data is 10 minutes. If the initial data was available at a higher sample rate, it was down-sampled to 10-minute intervals by block averaging the higher resolution data within each 10-minute block. Unless stated otherwise, all data is at a 10-minute sample time, such that there are 52704 data points in all year-long data sets. All data was normalized to the maximum load for 2008, 10754.5 MW. The various data sets at 5% penetration are plotted in Fig. 1, with daily averages substituted for the raw 10-minute data for clarity. The seasonal variability of the load, solar, and wave data sets is clear, while the wind generation appears to be much more seasonally uncorrelated.

Tidal energy conversion, which uses the moving water due to tidal variations to generate power, was not considered in this research. The tidal resource in the Pacific Northwest is strong for a few populous areas, such as Puget Sound. However, the overall tidal resource is not as large as wind, wave, and solar, and is much more geographically restricted. Future research will be extended to include tidal.

A. Wind

The wind power data used is for the approximately 1600 MW of wind within the BPA BAA for 2008. This includes roughly 15 wind farms throughout the Lower Columbia region [9]. The unadjusted power represents a 14% penetration, defined as the ratio of peak power to peak load demand over the year. The wind data is scaled directly as necessary to achieve the desired penetration rate for a given scenario.

B. Wave

The methodology for generating the wave data is described in detail in [10]. In short, the spectral significant wave height, dominant period, and dominant direction is collected from three different measurement buoys in the Pacific Northwest for 2008. Using the data from the measurement buoys, time-series water surface elevation data at a 0.4 second sample time for a 5 by 80 grid with 100 meter spacing is reconstructed. Each of the 400 locations in the grid is occupied by a 250 kW generic wave-following point-absorber wave energy converter. The converter power output is assumed to be proportional to the vertical water surface velocity squared. If the instantaneous power production exceeds 250 kW, it is clipped at that level. The proportionality is set such that the wave energy converter saturates at 250 kW regularly in sea state 6, which corresponds to significant wave heights of 4 meters or greater. The power from each of the three parks is then averaged over 10 minute intervals to generate the power time-series (52704 points). The power from the three locations is added together to produce the total wave power generation data. This total is then scaled as necessary to achieve the desired penetration rate for a given scenario.

C. Solar

Irradiance (power per area) data was gathered for 10 different locations in the Pacific Northwest from the University of Oregon Solar Radiation Monitoring Laboratory: Aberdeen, Ashland, Bend, Burns, Dillon, Eugene, Hermiston, Portland, Salem, and Twin Falls [11]. The data was processed to a 10 minute sample time over the 2008 calendar year.

It is assumed that each of the 10 locations is 50%...
photovoltaic (PV) and 50% concentrating solar (CSP). To generate the PV data, the irradiance is used directly without processing. For the concentrating solar data, a six hour thermal time constant is assumed. The irradiance data is run through a simple one-pole low-pass filter with a time constant of six hours. Both of these data sets are added together, each weighted at 50%, to generate the total output power for that site. Each of the 10 sites is then added together to produce the total solar data. Each site is weighted equally. This total is scaled as necessary to achieve the desired penetration rate for a given scenario.

IV. METHODOLOGY

In order to fully characterize both the variability and forecastability of various renewable energy resources, it is essential to define a consistent set of tools and methods that can be utilized for analysis.

A. Timescales for Reserve Requirements

While previous studies [12]-[14] have focused on examining correlation between various renewable resources and loads, this paper presents the results of an analysis on the impact of the variability of these resources on reserve requirements for a BAA. In order for a BAA to balance generation with load on a minute-by-minute, hourly, or daily basis, the variability of both the generation and the load must be examined. With renewable resources like wind, solar, and ocean wave, forecasting of the available generation can present a particular challenge, which, while having a large impact on the hourly or daily reserve requirements, often has less of an impact on the intra-hour requirements. Given the focus on reserve requirements, it readily becomes apparent that a clear understanding of the different types/timescales of reserves is necessary.

Three different timescales are currently used by the Bonneville Power Administration to calculate reserve requirements for the BAA [5]. The first, regulation, is defined as the difference between the minute-to-minute power generation/load and the 10-minute average power generation/load. This timescale accounts for small changes in power demand or supply that can be readily met through Automatic Generation Control (AGC) via spinning reserves.

The second timescale of interest, following, is defined as the difference between the 10-minute average power generation/load and the hourly average power generation/load. This timescale accounts for larger changes in the power demand or supply.

The final timescale, imbalance, is defined as the difference between the hourly average power generation/load and the forecasted generation/load for that hour. The imbalance component of the reserve requirements is directly impacted by the accuracy and frequency of the forecasted generation/load. With the large increase in wind power generation in BPA’s BAA over the 2010-2012 timeframe, the imbalance component of the reserve requirement is forecasted to grow rapidly given current forecasting tools and methods [5].

Both the following and imbalance reserve requirements are illustrated in Fig. 2. The available data for use in this paper was at a 10-minute sample time, so the regulation reserve component is not represented as it requires 1-minute sample time data. This should not affect the analysis as the regulation reserve requirement is consistently smaller than the following and imbalance reserve requirements due to the generally small minute-to-minute resource variability [5].

It should also be noted that some research groups have introduced the concepts of “variability” and “uncertainty” [6]. “Variability” refers to the natural variation in resource output, even if the forecast is accurate. “Uncertainty” refers to the difference between a perfect forecast and the actual forecast. These definitions are essentially the same as “following” and “imbalance” as defined above, respectively.

B. Forecasting

In order to calculate imbalance reserve requirements, the scheduled or forecasted power must be determined for both the renewable resource and the load.

For this paper, a one-hour persistence method is used to roughly approximate BPA’s wind forecasting methods. The one-hour persistence method predicts that the wind power generation for the next hour will be the same as it is when the forecast is made. The forecast is made at the 40 minute mark of the current hour and predicts that the power generation for the period beginning 10 minutes past the hour through 50 minutes past the hour will be the same as it currently is at 20 minutes prior to the hour. For example, if the current time is 12:40 and the current power generation is 200 MW, the prediction will be that the power generation between 1:10 and 1:50 will be 200 MW. Twenty minutes are allowed for ramping between one forecast period and the next (e.g. between 12:50 and 1:10 in the current example). The one-hour persistence method presents a simple and adequate baseline for forecasting the power generated by the wind. Its primary limitation is a lag in the forecast for rapidly increasing or decreasing wind power (i.e., ramps).

In order to keep the forecasting component from introducing bias in the results, the one-hour persistence method was used for all of the renewable energy resources in
this paper, including wind, solar, and ocean wave. It must be remembered, however, that in reality, forecasting for ocean wave power generation is likely to be much more accurate than forecasting for wind power generation given the long distances that waves travel before approaching the coastline [15]. There will also be differences in optimal forecasting for solar.

While the one-hour persistence method is viable as a baseline forecasting method for the highly variable renewable resources, using it as a method to forecast load is not optimal. The load curve follows a consistent pattern on a day-to-day basis, as seen in Fig. 3. This consistency allows for a much more accurate load forecast. While BPA utilizes a sophisticated load forecasting model that considers parameters such as temperature variation, historical load growth, and load variation on a daily, weekly, and seasonal basis [5], for the purposes of this paper a simple model was used.

In order to forecast load for 2008 (the period under study), historical load data for 2007 was used as a baseline. The 2007 data was processed to calculate each month’s average day (necessary given the seasonal variability in the shape of the daily load curve). For example, the load power time-series for the 24 hour period of December 1, 2007 (6*24 = 144 points) was averaged element-wise with the load power time-series for the 24 hour period of December 2, 2007 and so on for all days in December, 2007. The end result is a load power time-series that covers a 24 hour period (at a 10 minute sample time), and represents an average day of December 2007.

Unlike wind, the load is forecasted 10 minutes prior to the hour. The basic load forecast for the coming hour is forecasted as the average power over the hour for the corresponding hour in the previous year. For example, the basic forecasted power for the hour 2:10 to 2:50 (five data points at a ten minute sample time) on Dec. 1, 2008 is the average of the six data points 2:00 to 2:50 on Dec. 1, 2007. The power at 2:00 is determined as the midpoint of the linear ramp from the previous forecast at 1:50 to the forecast at 2:10.

A correction term is added to this basic forecast to account for the load-growth from one year to the next. This correction term is the difference in the hour-average power in the previous hour for 2007 and 2008. For example, the correction term added to the forecast for 2:10 to 2:50 Dec. 1, 2008 (as described above) is the difference between the average power for 1:00 to 1:50 Dec. 1, 2008 and 1:00 to 1:50 Dec. 1, 2007.

Finally, the algorithm uses a logic test to examine those situations where there is a transition between one month’s average day and the next to prevent discontinuities in the forecasted load. In these situations, a simple 1-hour persistence forecast is used for the scheduled load for that transition hour.

The total forecast for the net load (load minus renewable generation) is simply the sum of the forecasts for each component: load, wind, wave, and solar.

C. Following and Imbalance Calculations

Utilizing the forecasting methods in the previous section, it is then possible to process the 2008 data to calculate the following and imbalance reserve requirements. Moving through each hour of 2008, the difference between each 10-minute power and the hourly average power was computed (following) and the difference between each hourly average power and the scheduled/forecasted power was computed (imbalance). Both the following and imbalance components were stored in an array for ease of access and analysis.

Industry-standard practice for computing reserve requirements involves sorting the following and imbalance calculated reserves and then keeping the middle 99.5% of the data points, eliminating the top and bottom 0.25% of outliers. According to BPA, this trimming of the data still enables the controllers to meet the necessary North American Electric Reliability Corporation (NERC) and Western Electricity Coordinating Council (WECC) reliability guidelines for balancing power supply and demand, while eliminating those extremely rare events where required reserves are beyond three standard deviations from the mean [5], [16].

The plot in Fig. 4 demonstrates the various data sets for wind power generation for an example one-day period in 2008. The solid line in the plot is the collection of actual combined wind power generation for the BPA BAA. The dashed line is the hourly average power (an average of the six 10-minute data points for that hour). The dash-dot line is the...
scheduled/forecasted power for the hour.

The plot in Fig. 5 demonstrates the following and imbalance reserve calculations for the load demand for the same one-day period. The top plot of Fig. 5 shows the actual load, hourly average load, and forecasted load (similar to Fig. 4), while in the bottom plot, the calculated following and imbalance reserve components are illustrated. As an example, for the period starting at time marker 2040, it is easy to see that the forecasted load was too low, creating a negative growth in the imbalance plot below. In comparison to the plot in Fig. 4, this same time-period demonstrates an over-forecast in the wind generation. These plots clearly show how the one-hour persistence method can cause the imbalance reserve requirements to be larger than the following reserve requirements. In comparison, it is clear that the load forecast in Fig. 5 is generally much more accurate than the wind forecast in Fig. 4. This is simply due to the much more predictable nature of the load demand curve.

The plots in Fig. 6 show the following and imbalance reserve calculation for load minus wind, or load demand minus generated wind power, for the same one-day period in 2008. The artifice of load minus wind, or load minus resource as will be discussed herein, is useful in order to better examine the impact of the renewable resource on the power system. At low penetration levels, the power generation from renewable resources looks similar to a negative load to the system operator, and it can thus be treated in this manner.

Of particular interest in a comparison between Fig. 4, Fig. 5, and Fig. 6 is how close the scheduled/forecasted power is to the actual load minus wind line in Fig. 6 versus the larger discrepancy between the two in Fig. 4. This difference is due to the limited impact that the relatively small wind power generation (on the order of 0.05 to 0.1 pu) has on the much larger load demand (on the order of 0.5 to 0.8 pu). Even though the forecast for the wind generation is much less accurate than the load forecast, when the two are combined the wind forecast has relatively little impact. It is essential to note, however, that these plots demonstrate 2008 data, with a maximum installed wind capacity of ~1,600 MW [9]. With the expected rapid growth of installed wind capacity to over 6,000 MW, the impact of the wind forecast on the imbalance requirement will grow. This is discussed further in the results section below.

V. RESULTS

The following and imbalance reserve requirement distributions that were generated from the load, wind, solar, and wave data for the various scenarios are characterized by the statistics presented in Table I and Table II, respectively. The first data column in each table represents the base load reserve requirement for each timescale. This can be directly compared to the second data column, which presents the load minus 15% wind scenario. This scenario most closely

<table>
<thead>
<tr>
<th>Load Minus …</th>
<th>Load</th>
<th>15% Wind</th>
<th>10% Wind + 5% Solar</th>
<th>10% Wind + 5% Wave</th>
<th>10% Wind + 2.5% Solar + 2.5% Wave</th>
<th>5% Wind + 5% Solar + 5% Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.02759</td>
<td>-0.02925</td>
<td>-0.02858</td>
<td>-0.02858</td>
<td>-0.02860</td>
<td>-0.02831</td>
</tr>
<tr>
<td>Max</td>
<td>0.02124</td>
<td>0.02336</td>
<td>0.02212</td>
<td>0.02213</td>
<td>0.02209</td>
<td>0.02155</td>
</tr>
<tr>
<td>Variance</td>
<td>3.7342e-005</td>
<td>4.4216e-005</td>
<td>4.0867e-005</td>
<td>4.0515e-005</td>
<td>4.0522e-005</td>
<td>3.8710e-005</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.27944</td>
<td>-0.24924</td>
<td>-0.24468</td>
<td>-0.27483</td>
<td>-0.26090</td>
<td>-0.25293</td>
</tr>
<tr>
<td>MAE</td>
<td>0.00437</td>
<td>0.00483</td>
<td>0.00464</td>
<td>0.00460</td>
<td>0.00461</td>
<td>0.00449</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.00611</td>
<td>0.00665</td>
<td>0.00639</td>
<td>0.00637</td>
<td>0.00637</td>
<td>0.00622</td>
</tr>
</tbody>
</table>
represents the current renewable resource portfolio in the Pacific Northwest. On both the following and imbalance timescales (particularly the imbalance timescale), the deleterious effect of wind on utility reserve requirements is obvious. The minimum (min) and maximum (max) are the necessary reserve requirement to cover the variability for a given timescale (following or imbalance). Comparing the first column (only load), with second column (load minus 15% wind penetration), the variability added by wind to the net load increases the reserve requirements. For example, for the imbalance timescale, the increasing reserve required for the load alone is calculated to be 379.3 MW, while for the load minus 15% wind it is 433.0 MW, and for the load minus 5% wind, 5% solar, and 5% wave, it is 398.3 MW. Thus, with the diversification of renewable resources, the reserve requirement is improved compared to the wind alone case.

The mean absolute error (MAE) and root mean square error (RMSE) both increase significantly for 15% wind penetration. More significant is that the RMSE increases more than the MAE. Because larger errors are weighted more heavily in the RMSE, this implies an increase in the number of events requiring larger reserves. The variance also increases.

The next data column presents the load minus 10% wind and 5% solar scenario. Comparing the results in this column to those for the load minus 15% wind distributions, it is obvious that by adding a second large-scale renewable resource to the portfolio, the reserve requirements on both the following and imbalance timescales are reduced. This result is also borne out by the results in the next data column, which presents the load minus 10% wind and 5% wave scenario.

Similar results are demonstrated in the fifth data column, presenting the load minus 10% wind, 2.5% solar, and 2.5% wave scenario. The statistics for the following and imbalance distributions for this scenario fall between those for the previous two scenarios, as expected given the equal mix of wind and solar penetration.

The final data column proves to be the most illuminating, however. In this scenario, an equal mix of 5% wind, 5% solar, and 5% wave penetration is subtracted from the load. This diverse renewable resource portfolio provides the largest benefit to the reserve requirements for both the following and imbalance timescales compared to any of the other scenarios, especially the current portfolio of wind alone.

For the equal mix scenario, the variance of both distributions is very close to those of the load alone. Particularly for the imbalance reserve requirement distribution, the increased diversity of renewables is most helpful in reducing both the MAE and the RMSE. In fact, unlike the load minus 15% wind scenario where the RMSE increased more than the MAE compared to the load alone, the RMSE and MAE increased the same amount in the equal mix scenario, implying that the addition of the diverse renewables did not cause a disproportionate increase in the number of events requiring larger reserves. From a utility perspective, this is an important difference from the current portfolio of wind alone.

Another interesting observation is in the skewness. In all cases the skewness is negative, which means that the net load (load minus renewable generation) is less than forecasted more often than not. This could be caused by a tendency to over-forecast the load, or under-forecast the renewable generation. The practical significance is that utility operators will need decreasing reserve available more often than increasing reserve. Also, the addition of variable, renewable generation tends to decrease the skewness.

VI. CONCLUSION

The results of the analyses in this study have confirmed the hypothesis that the various characteristics of wind, wave, and solar generation will allow a greater combined penetration rate than using only one predominate type of renewable power source. By utilizing an equal mix of wind, solar, and wave power generation, the overall reserve requirements are reduced compared to those for wind alone. Unfortunately, the current portfolio of renewable resources in the Pacific Northwest is almost exclusively composed of wind generation. In the near future, the situation is only expected to grow more severe as more and more wind generation is installed. By diversifying the portfolio, the increasing strain on BAA reserves can be lessened. Diversification, however, would require significant resources to implement wave and solar generation technologies on a scale as large as the current level of wind penetration.

Opportunities for future work abound in this research area. Improvement in forecasting accuracy alone can greatly help the imbalance reserve requirements. Possibilities for future study include the investigation of the impact of adding other renewable generation sources such as tidal power to the mix,
as well as a study to determine the optimal combination of the various renewable resources to improve reserve requirements even further.

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VIII. REFERENCES

IX. BIOGRAPHIES
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