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 nondispatchable. 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*—Load forecasting, load modeling, marine technology, power systems, power system stability, reserve requirements, solar power generation, wind power generation.**

NOMENCLATURE

BPA	Bonneville Power Administration.
BAA	Balancing Authority Area.

I. INTRODUCTION

MANY balancing areas within the U.S. are faced with a rapidly expanding wind power resource. For example, it is predicted that as much as an additional 5000 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 interhour 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.

Manuscript received September 14, 2010; revised January 04, 2011; accepted February 07, 2011. Date of publication February 17, 2011; date of current version June 22, 2011. This material is based upon work supported by the National Science Foundation under Grant 0846533.

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Digital Object Identifier 10.1109/TSTE.2011.2114902

Wind power is now a very mature and established renewable resource throughout the world. However, other renewable power sources such as solar (photovoltaic (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. [3], [4].

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 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 megawatts, may go from full output to low production or vice versa over several hours [5].
2) Nondispatchable: 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. At low to moderate levels, renewable power generation appears as a negative load.
3) Energy source: Due to the nondispatchable nature of wind, solar, or wave, they generally have a relatively low capacity credit [6]–[9]. 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, nondispatchable nature of wind, wave, and solar has a significant impact on the utility reserve requirements [10]. 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.

1949-3029/$26.00

C. Research Objective

A number of research groups have analyzed the impact of large-scale wind integration on utility operation, including reserve requirements [11], [12]. Some research has also been extended to include large-scale solar [13]. Reference [14] demonstrates a technical method for reserve requirement calculation for high levels of renewable power penetration in general. The research presented in this paper analyzes the reserve requirements for the Pacific Northwest of the U.S. including wind, solar, and ocean wave energy specifically, using actual load and wind power data, and solar and ocean power data generated from resource measurements. The supposition 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. For all scenarios, wind penetration is greater than or equal to either wave or solar, as this more closely reflects reality for the Pacific Northwest, where a large and growing wind capacity is already in place.

If the supposition 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.

This paper builds off of [15] by adding enhancements to the wave power data generation methodology and further advancing the analysis of the reserve requirement calculations. Reference [16] investigates a parallel branch of research, quantifying the increase in reserve requirement as a function of penetration, whereas this paper focuses on the impacts of diversification.

II. 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 (BPA) Balancing Authority Area (BAA). Wind and load data for the BPA BAA are both freely available directly from BPA [17]. The solar and ocean wave data were generated, as described below. All data, and the analysis, covers the calendar year 2008 starting January 1. The sample time for the load, wind, solar, and wave power data is 10 min. If the initial data was available at a higher sample rate, it was down-sampled to 10-min intervals by block averaging the higher resolution data within each 10-min block. Unless stated otherwise, all data is at a 10-min sample time, such that there are 52 704 data points in all year-long data sets. All data was normalized to the maximum load for 2008, 10 754.5 MW. The various data sets at 5% penetration are plotted in Fig. 1, with daily averages substituted for the raw 10-min 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.

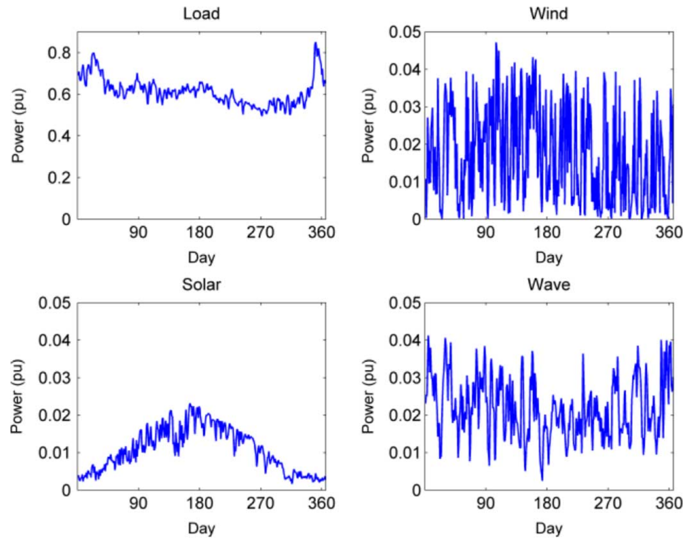

Fig. 1. Plots of year-long data (averaged daily) for load, wind, solar, and wave power. The wind, solar, and wave power plots are at a 5% penetration level.

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 [18]. 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 [19]. 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 0.5-s sample time for a 5 by 80 grid with 100-m 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 combined output of the wave energy converters produces a capacity factor of 50% for an average winter day (e.g., a day in January). The power from each of the three parks is then averaged over 10-min intervals to generate the power time-series (52 704 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 [20]. The data was processed to a 10-min sample time over the 2008 calendar year.

It is assumed that each of the 10 locations is 50% 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[1] [21]. 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.

III. 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. Time Scales for Reserve Requirements

While previous studies [22]–[24] have focused on examining the 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/time scales of reserves is necessary.

Three different time scales are currently used by the BPA to calculate reserve requirements for the BAA [11]. The first, *regulation*, is defined as the difference between the 10-min average power generation/load and the minute-to-minute power generation/load. This time scale accounts for small changes in power demand or supply that can be readily met through Automatic Generation Control (AGC) via spinning reserves.

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

The final time scale, *imbalance*, is defined as the difference between the hourly forecasted generation/load and the hourly average power 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 time frame, the imbalance component of the reserve requirement is forecasted to grow rapidly given current forecasting tools and methods [11].

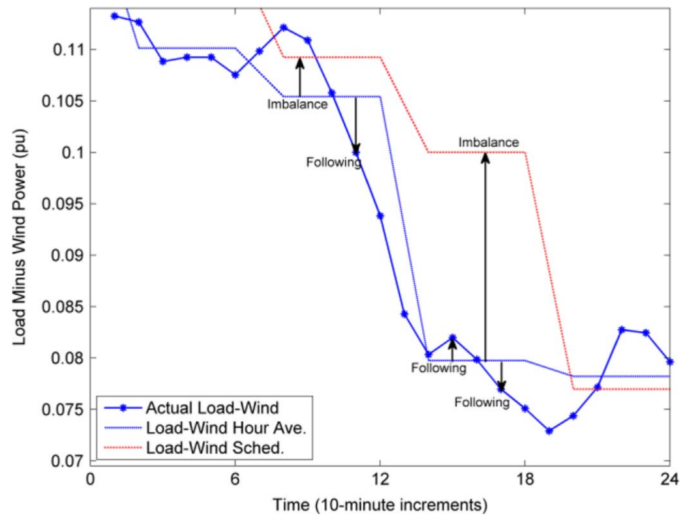

Fig. 2. Definition of following (difference between 10-min and hour averages) and imbalance (difference between hour average and forecasted/scheduled) reserve requirements.

Both the following and imbalance reserve requirements are illustrated in Fig. 2. The available data for use in this paper was at a 10-min sample time, so the regulation reserve component is not represented as it requires 1-min 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 [11].

It should also be noted that some research groups have introduced the concepts of "variability" and "uncertainty" [12]. "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.

In practice, more advanced forecasting methods that include real-time meteorological measurements can provide improved forecasting over persistence methods [25]. However, 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. For relatively short forecasting horizons, persistence methods are reasonably accurate, and simple to implement.

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

[1]A time constant of six hours was chosen as a conservative estimate to include molten-salt, oil-based, and unspecified CSP systems. Some systems, in particular molten-salt-based systems, may offer longer energy storage times. This may decrease the solar reserve requirements. An analysis on the reserve requirements impact as a function of CSP storage time is a good topic for future research.

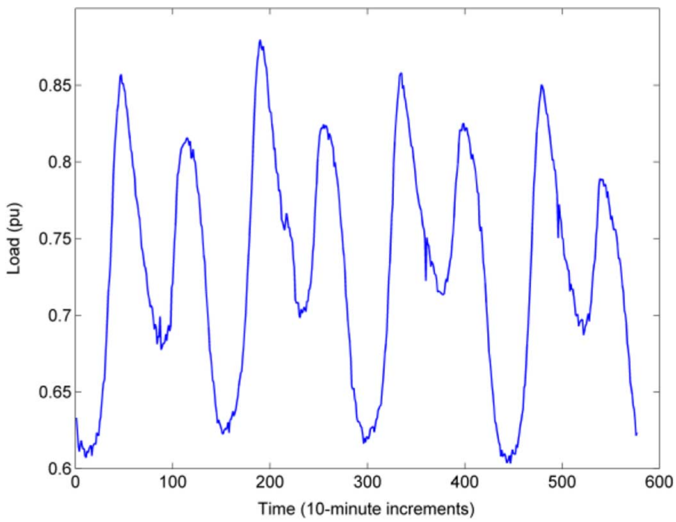

Fig. 3. Load variation over a four-day period in January 2008 [17].

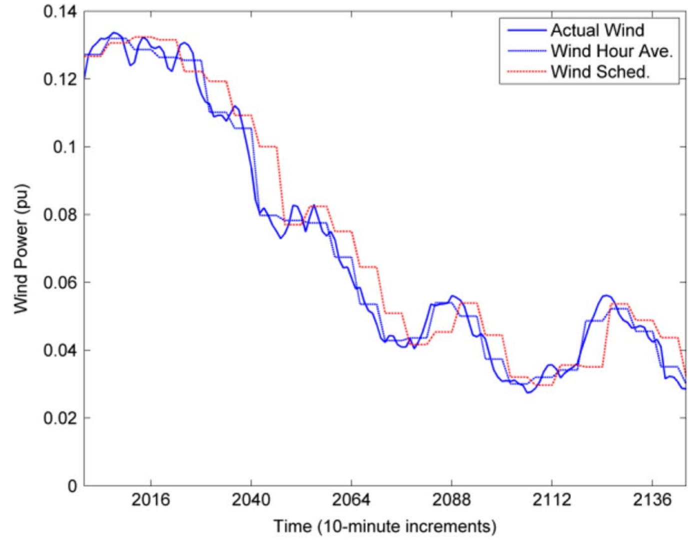

Fig. 4. Example of comparison between wind power output versus hourly average versus scheduled output.

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 [11], 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-min sample time), and represents an average day of December 2007.

Unlike wind, the load is forecasted 10 min prior to the hour. The basic load forecast for the coming hour is the average power over the hour for the corresponding hour in the previous year average day for that month. For example, the basic forecasted power for the hour 2:10 to 2:50 (five data points at a 10-min sample time) on December 1, 2008 is the average of the six data points 2:00 to 2:50 for the average December day of 2007, as described in the preceding paragraph. 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 December 1, 2008 (as described above) is the difference between the average power for 1:00 to 1:50 December 1, 2008 and 1:00 to 1:50 December 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-h 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 the hourly average power and each 10-min power was computed (following) and the difference between the scheduled/forecasted hourly power and each hourly average 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 [11], [26].

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-min data points for that hour). The dashed–dotted 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

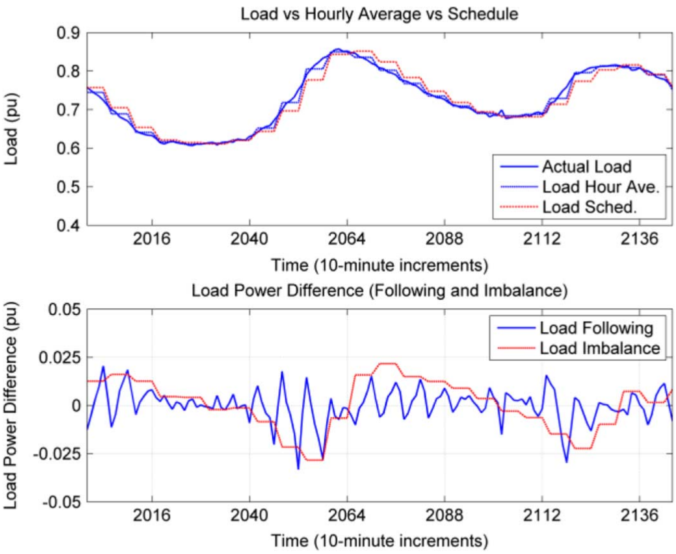

Fig. 5. Example of comparison between load demand versus hourly average versus scheduled demand with calculated instantaneous following and imbalance reserve requirements. The final reserve requirement is the maximum and minimum of the bottom curve over the entire year, excluding the top and bottom 0.25% outliers.

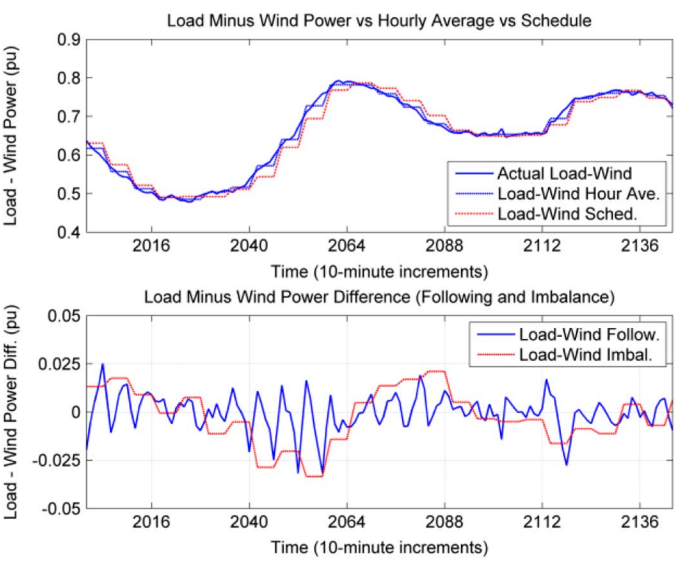

Fig. 6. Example of comparison between load minus wind versus hourly average versus scheduled demand with calculated instantaneous following and imbalance reserve requirements. The final reserve requirement is the maximum and minimum of the bottom curve over the entire year, excluding the top and bottom 0.25% outliers.

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.

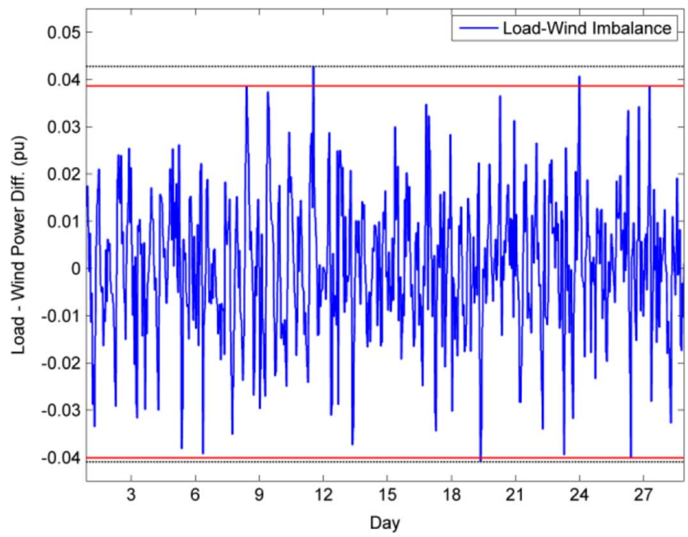

Fig. 7. Example of load minus wind imbalance over four weeks. The dashed–dotted black lines represent the overall maximum and minimum reserve requirement, and the red solid lines represent the maximum and minimum reserve requirement excluding the top and bottom 0.25% of outliers.

To better clarify the calculation of the reserve requirements, Fig. 7 demonstrates an example of the imbalance reserve over a four-week period with the actual maximum and minimum values denoted by the black dashed–dotted lines. Upon application of the outlier trimming procedure, the red solid lines represent the new maximum and minimum imbalance reserve requirement values that exclude the top and bottom 0.25% of outliers. Note that in this context, maximum and minimum refer to the most positive and most negative values for the reserve, which correspond to the need for the system operator to decrease or increase generation, respectively, discussed further in Section V. For this specific example, the actual maximum imbalance requirement is 0.0428 pu, while the "trimmed" requirement is 0.0386 pu. It is the "trimmed" reserve requirement that is used for planning purposes and that is discussed in Section V.

Of particular interest in a comparison between Figs. 4, 5, and 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. Nevertheless, comparing the bottom plots in Figs. 5 and 6, it is apparent that the addition of the wind has had an effect on the following and imbalance reserve requirements. For example, the maximum following requirement is larger in Fig. 6 than it is in Fig. 5.

It is essential to note, however, that these plots demonstrate 2008 data, with a maximum installed wind capacity of ∼1600 MW [18]. With the expected rapid growth of installed

TABLE I
RESULTS FOR FOLLOWING RESERVE REQUIREMENTS DISTRIBUTION (PU, Pbase = 10754.5 MW)

		Load Minus …				
	Load	15% Wind	10% Wind + 5% Solar	10% Wind + 5% Wave	10% Wind + 2.5% Solar + 2.5% Wave	5% Wind + 5% Solar + 5% Wave
Min	-0.02759	-0.02950	-0.02878	-0.02885	-0.02868	-0.02853
Max	0.02124	0.02378	0.02229	0.02273	0.02254	0.02185
Variance	3.7342e-005	4.5377e-005	4.1385e-005	4.1662e-005	4.1200e-005	3.9427e-005
Skewness	-0.27944	-0.23975	-0.24129	-0.26619	-0.25820	-0.24867
MAE	0.00437	0.00489	0.00467	0.00468	0.00465	0.00455
RMSE	0.00611	0.00674	0.00643	0.00645	0.00642	0.00628

TABLE II
RESULTS FOR IMBALANCE RESERVE REQUIREMENTS DISTRIBUTION (PU, Pbase = 10754.5 MW)

		Load Minus …				
	Load	15% Wind	10% Wind + 5% Solar	10% Wind + 5% Wave	10% Wind + 2.5% Solar + 2.5% Wave	5% Wind + 5% Solar + 5% Wave
Min	-0.03992	-0.04454	-0.04048	-0.04214	-0.04115	-0.03960
Max	0.03527	0.04159	0.03876	0.03693	0.03735	0.03832
Variance	1.0515e-004	1.5190e-004	1.2898e-004	1.2767e-004	1.2677e-004	1.1532e-004
Skewness	-0.30070	-0.16913	-0.10718	-0.26165	-0.18798	-0.13444
MAE	0.00759	0.00939	0.00865	0.00857	0.00854	0.00813
RMSE	0.01025	0.01233	0.01136	0.01130	0.01126	0.01074

wind capacity to over 6000 MW, the impact of the wind forecast on the imbalance requirement will grow. This is discussed further in Section V.

IV. 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 Tables I and II, respectively. The first data column in each table represents the base load reserve requirement for each time scale. This can be directly compared to the second data column, which presents the load minus 15% wind scenario. This scenario most closely represents the current renewable resource portfolio in the Pacific Northwest. On both the following and imbalance time scales (particularly the imbalance time scale), the deleterious effect of wind on utility reserve requirements is obvious.

The minimum (min) and maximum (max) are the largest differences over the year between the hour average and 10-min average (for following, Table I) and the hourly forecast and hourly average (for imbalance, Table II), after the top and bottom 0.25% of outliers are removed. The max and min represent the necessary reserve requirement to cover the variability for a given time scale (following or imbalance). The minimum row, being negative, represents cases in which there was less renewable generation than expected, or greater load than expected, or some combination of both. Therefore, the system operator must increase dispatchable generation elsewhere in the system to cover the deficit. This is called *incremental* reserve. Similarly, the maximum row, being positive, corresponds to cases in which the renewable generation is greater than expected, or the load is less than expected, or a combination of both. The operator must decrease dispatchable generation to balance the system. This is the *decremental* reserve.

Comparing the first column (only load), with the 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 time scale (Table II), the decremental reserve required for the load alone is calculated to be 379.3 MW (0.03527 pu), while for the load minus 15% wind it is 447.3 MW (0.04159 pu), and for the load minus 5% wind, 5% solar, and 5% wave, it is 412.1 MW (0.03832 pu). These numbers represent the maximum amount over the year by which the forecasted net load exceeded the actual net load, and thus the necessary amount of decrease of dispatchable generation to accommodate the over-forecast (i.e., decremental reserve). 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

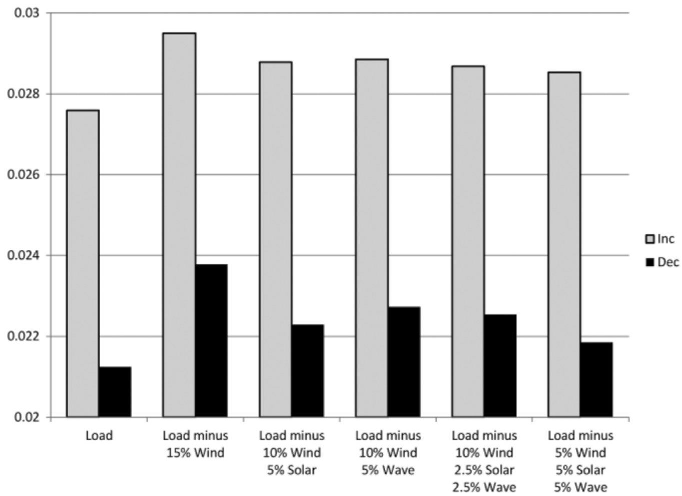

Fig. 8. Comparison of incremental and decremental following reserve requirements (per unit) for each of the six scenarios analyzed.

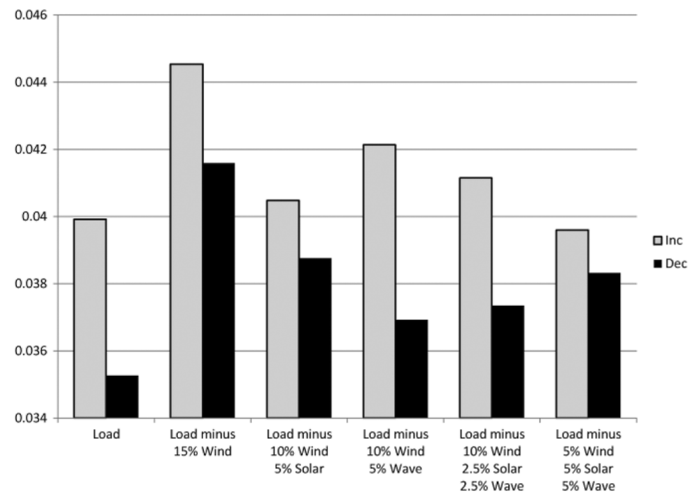

Fig. 9. Comparison of incremental and decremental imbalance reserve requirements (per unit) for each of the six scenarios analyzed.

adding a second large-scale renewable resource to the portfolio, the reserve requirements on both the following and imbalance time scales 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 incremental and decremental reserve requirements for the following and imbalance distributions for this scenario fall between those for the previous two scenarios, as expected given the equal mix of solar and wave 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 time scales 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 approximately 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 decremental reserve available more often than incremental reserve. Also, the addition of variable, renewable generation tends to decrease the skewness.

A summary of the reserve requirements for the six analyzed scenarios is presented in Figs. 8 and 9. In these two charts, the label "inc" refers to the incremental reserve requirement and the label "dec" refers to the decremental reserve requirement. For the following case in Fig. 8, the difference between the various scenarios is relatively small, with the important note that all of the scenarios with a combination of renewable resources require fewer reserves than that with wind alone. In the imbalance case in Fig. 9, however, the differences become much more apparent. In general, as the renewable resource contribution becomes more diversified, the imbalance reserve requirement tends to decrease.

V. Conclusion

The results of the analyses in this study lend evidence to the confirmation of the supposition 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.

ACKNOWLEDGMENT

The authors would like to thank B. Koehler, D. Lozovoy, and J. Bermejo of the BPA for their technical assistance. The authors would also like to thank Dr. T. Ozkan-Haller of Oregon State University for her assistance with the wave data generation code.

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