

AN ABSTRACT OF THE THESIS OF

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Increased penetration of renewable energy sources results in higher operating reserve requirements, due to the inherent variability and uncertainty of these resources. Many studies, primarily focusing on wind and solar, have determined that geographic diversity of variable renewables substantially reduces system variability and uncertainty. The Pacific Northwest is well suited to the addition of wave and tidal energy to its renewable portfolio. This study compares the varying reserve requirements with geographically diverse combinations of wind, solar, wave and tidal sources; a total renewable penetration of thirty-six percent was selected for the analysis. The different groups of test scenarios consistently demonstrate reduced reserve requirements with geographic diversity. The best combination of renewable sources incorporated wind, solar, wave and tidal; all except tidal geographically diverse. The reserve requirements for this scenario were relatively close to the baseline of no renewables, demonstrating the advantages of a diverse mix of renewable sources.

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Aggregated Reserve Requirements
of Geographically Diverse Renewable Portfolios
in the Pacific Northwest

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TABLE OF CONTENTS

	<u>Page</u>
I. Introduction.....	1
A. Reserve Requirements.....	1
B. Variable Renewable Energy Sources.....	4
C. Impact of Geographic Diversity on Variable Renewables.....	6
II. Methods.....	11
A. Data Collection/Generation.....	11
B. Data Analysis.....	13
III. Results.....	15
IV. Discussion.....	17
V. Conclusions and Future Work.....	19
VI. References.....	20

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.	Following Reserve Requirements.....	15
2.	Imbalance Reserve Requirements.....	15

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I.	Renewable Source Penetrations.....	13
II.	Trimmed Following and Imbalance Reserve Requirements.....	16

I. INTRODUCTION

The use of renewable energy is increasing for multiple social, political and economic reasons. Although the benefits of renewable energy are well understood in the general population, its widespread use also creates technical challenges requiring significant effort in the power utility industry. The traditional power grid consists of centralized, synchronous, dispatchable generation, with relatively predictable loads based on history and weather conditions. Generation and load must be continuously balanced for the power system to perform reliably. The introduction of variable renewable energy sources into the traditional power grid complicates this balance between generation and load, especially as the penetration of renewables increases.

The North American Electric Reliability Corporation (NERC) defines a Balancing Authority (BA) as the responsible party for balancing the generation and load in its Balancing Authority Area (BAA) [1]. The regional BA in the Pacific Northwest is the Bonneville Power Administration (BPA). The BPA service area is approximately 300,000 square miles [2], and includes Oregon, Washington, Idaho, western Montana, and small parts of eastern Montana, California, Nevada, Utah and Wyoming [3]. Renewable portfolio standards within the BPA BAA include: Oregon with 25% of electric energy needs to be met using renewable sources by 2025 [4]; Washington with 15% by 2020 [5]; California with 33% by 2020 [6]; Montana with 15% by 2015; Nevada with 25% by 2025; and Utah with a goal of 20% by 2025 [7].

A. Reserve Requirements

Higher penetration of renewable sources will require increased operating flexibility to maintain a balanced power system, with available methods including

dispatchable generation, adjustable demand, energy storage and power import/export. In addition, a system of reserves must be maintained to compensate for the variability (natural variation in generation output) and uncertainty (difference between the forecasted and actual generation and load). Reserves are capacity (generation, responsive load, or storage), under system operator control, that is capable of ramping up (incremental or inc) or down (decremental or dec) to maintain system balance. Operating reserves may be classified in different ways, but the method used by the National Renewable Energy Laboratory (NREL) first looks at whether the reserves are deployed for normal or event conditions. Normal conditions can be based on both variability and uncertainty, but are continuously taking place, while events are severe and rare. The non-event reserve is then separated by speed of response, with regulating reserve being faster and following reserve being slower. The event reserve is also separated by speed of response, with contingency reserve available for the quick response to a sudden event such as a large supply loss or transmission line failure. Ramping reserve is used for rare events that are not instantaneous in nature [1].

Specific reserve requirements vary from region to region, based on both reliability standards and physical differences between regions. Reserve requirements cannot be analyzed in isolation, they must be analyzed within the context of the specific power system including the impacts of all variable resources. BPA's balancing reserve capacity requirements consist of three components: regulating reserve, following reserve, and imbalance reserve. Regulating reserve is the capacity necessary to provide for the continuous balancing of resources and load on a moment to moment basis. Following reserve is the capacity to meet within hour shifts of average energy due to variations of

actual load and generation from forecast load and generation (the difference between the hourly average power generation/load and the ten minute average power generation/load). The imbalance reserve refers to the impact on the following reserve amount due to the difference (imbalance) between the average scheduled energy over the hour and the average actual energy over the hour [8]. Following and imbalance reserves may be viewed as representing the variability and uncertainty respectively.

In practice, it is also necessary to distinguish between spinning reserve and non-spinning reserve. Spinning reserve is defined as unloaded generation that is synchronized and ready to serve additional demand. Non-spinning reserve is generating reserve not connected to the system, but capable of serving demand within a specified time, or interruptible load that can be removed from the system in a specified time [1]. NERC requires that at least 50% of operating reserve obligation be met with spinning capacity responsive to Automatic Generation Control (AGC). NERC also requires that 100% of regulating reserve must be carried on units with spinning capacity responsive to AGC. The categories of following and imbalance reserves do not have NERC defined criteria; therefore, BPA has defined its own criteria. BPA carries at least 50% of the inc following reserve as spinning, and up to 50% as non-spinning. For imbalance, up to 100% of the inc obligation may be met with non-spinning capability. By definition, all dec reserves are spinning, because units must be generating in order to deploy dec reserves [8].

The rationale for carrying at least 50% of the inc following requirement as spinning is to provide sufficient response over the first five minutes of movement while also providing enough time to synchronize non-spinning units and ramp the units through their rough zones. Synchronization generally takes about three minutes, with the unit

fully ramped in over the next seven minutes. If additional reserves are required to cover a growing imbalance, additional units are synchronized and ramped as the following reserve is consumed and the imbalance reserve is deployed with non-spinning capacity [8].

B. Variable Renewable Energy Sources

The renewable energy sources included in this study are wind, solar, wave and tidal; it is generally agreed that higher penetrations of these variable, non-dispatchable sources will create an increase in the total amount of operating reserves held in power systems [9]. Geothermal, biomass and traditional hydropower are excluded as they are dispatchable energy sources with reserve requirement impacts similar to traditional thermal generation sources.

Wind energy generation uses wind turbines to convert the kinetic energy of the wind into electricity; compared to other renewable sources, wind energy is a relatively mature technology. In the Pacific Northwest, the capacity of wind power generating facilities reached more than 7,900 MW in 2012 [10]. Forecasts indicate that the amount of installed wind capacity in the area could reach as much as 10,000 MW by 2020. Most of these wind projects are geographically concentrated in the Columbia River Plateau. This concentration produces large unexpected swings in aggregate power output, requiring BPA to provide significant balancing reserves [11]. The federal hydro system has been the principle source of balancing reserves for managing these wind fluctuations, but BPA has already experienced situations where the limited supply of the federal hydro has been exhausted [12]. The seasonality, weather dependence and environmental constraints of the hydro system only add to the complexity. To reliably integrate the

output of a growing wind fleet, BPA states that it is vital to expand balancing capabilities and reserves [11].

There are two general categories of large scale solar technologies: solar photovoltaic (PV) and concentrating solar power (CSP). PV employs a semiconductor material to convert sunlight into direct current electricity; an inverter transforms this DC into AC for grid applications. Flat plate PV can take advantage of direct and indirect insolation, so PV modules need not directly face and track incident radiation, giving PV systems a broad geographical application [13]. CSP plants need high direct normal insolation for efficient operation, so they are typically only built in those favorable regions. Since the geographic location of the Pacific Northwest does not provide optimal conditions for CSP, this study focuses on PV only. On partially cloudy days, individual large PV plants may vary by 70% of their capacity, creating significant integration challenges [14].

The typical definition of wave energy is the kinetic and potential energy contained in the waves that propagate across the ocean surface. Wave energy converters (WECs) are the devices that convert this kinetic and potential energy into electricity [15]. Different approaches to WEC design are still being developed and tested. A wave spectrum is a plot of wave energy against period, and can be used to derive the significant wave height (H_s) and peak period (T_p); the power output of a WEC can be estimated from these sea state parameters. Oregon and Washington both have coastlines with significant potential to harness wave energy.

Ocean tides are created by solar and lunar gravitational forces combined with the rotation of the earth. This rise and fall of ocean water creates an incoming and outgoing

flow of water in bays, estuaries, etc., and can be amplified by coastline topography in specific locations. A few locations in the United States, including the state of Washington, have the potential for significant local generation [15]. There are two general approaches for tidal energy extraction, a barrage approach (using conventional hydro turbines in a structure) and a hydrokinetic approach. Since a barrage approach would have significant environmental issues, only the hydrokinetic approach is included in this study. The hydrokinetic method places turbines to capture the horizontal flow of tidal currents. These turbines are similar in concept to wind turbines, adjusted to operate in the higher density of salt water.

C. Impact of Geographic Diversity on Variable Renewables

The ability to create accurate forecasts of renewable generation is critical for effective integration. Wind power forecasts are usually most accurate when using the persistence scheduling method (establishing a schedule based on the output at a specific time prior to the delivery period) [1]. Solar power forecasting can be based on the predictable clear-sky output [13]. Both wave and tidal energy offer prediction of power output with the potential to be significantly more reliable than currently available for wind or solar. Accurate forecasting is essential for commercial marine traffic, so the models and infrastructure already exist, with good quality forecasts available publicly [15].

In principle, the reserve requirement impacts of utilizing variable energy sources can be determined by modeling the power system both with and without these variable sources. The difference in required reserves is then the incremental reserves required with

these renewable sources. It is important to have synchronized time-series data, as weather patterns affect both loads and renewable generation [15].

Many studies have analyzed the impact of increased variable generation on reserve requirements, with the majority evaluating the impact of wind and/or solar generation. Two studies are particularly noteworthy: the Eastern Wind Integration and Transmission Study and the Western Wind and Solar Integration Study [15]. It is difficult to succinctly discuss and compare quantitative results between studies, as the magnitude of the effects of geographic diversity will depend on the amount of wind generation relative to load, the variability of load alone, and the amount of diversity of the aggregate wind generation. Both variability and uncertainty of aggregate wind decrease percentage-wise with more wind and larger geographic areas [16]. The Eastern Wind Integration and Transmission Study states that geographic diversity “quite substantially” reduces system variability and uncertainty [17].

Many other studies have reached similar conclusions. Describing geographic diversity slightly differently, the correlation between wind power output patterns at different sites decreases as the distance between the sites increases. This smoothing characteristic is particularly apparent at short time scales [18]. One wind turbine could vary quite a bit on a minute to minute basis; however, because the minute-to-minute variability of individual wind turbines are not correlated, the per unit output of multiple turbines aggregated into a wind plant is much less variable in this time frame. A large number of plants that are not geographically close to one another will achieve even further decreases in per unit variability. Therefore, the relative regulating reserves required are lower for larger BAs than smaller BAs [1].

Solar plants similarly benefit from geographic diversity. Solar generation has a bell shape throughout the course of a sunny day, but can vary rapidly with different weather phenomena (clouds, ambient temperature, or precipitation) [8]. The relevant characteristics of solar generation are the output variability and rate of change over different time periods, and the predictability of these events. The variability and predictability of aggregated solar depends on the degree of correlation of cloud-induced variability between solar plants, which in turn depends on the specific locations of the solar plants and the regional characteristics of cloud patterns. Generally, the variability of solar plants that are farther apart is less correlated, and variability over shorter time periods is less correlated than variability over longer time periods [13]. A small PV plant might see high variability from clouds, but the impact on the bulk power system is minimal. In contrast, a large plant can have a higher impact on the bulk power system, but its larger area helps to smooth out the variability. With additional PV plants, the geographic diversity of the plants and the improbability of cloud fronts obscuring all PV plants at the same time result in further smoothing [19].

Although wave energy is highly seasonal, it provides a higher level of predictability than wind or solar, reducing the potential for unexpected ramping of power output. The short-term water surface elevation changes rapidly, but the statistically represented sea state as a whole varies much more slowly over longer periods, generally hours for significant differences. Since commercial wave power generation is expected to occur in arrays of units, some variability issues are expected to become less of a challenge as very short time frame variability is smoothed out by the spatial distribution of devices within the resource [15]. A recent study in the Pacific Northwest observed that

aggregation of modeled power output from five sites reduced extreme variability events at shorter timescales (one minute to one hour), although there was a high level of correlation between study locations at a daily timescale [20].

At a practical level, significant geographic diversity for tidal power may be difficult to achieve, due to limited areas with the ideal geographical characteristics for tidal power production. The output from tidal turbines will vary from rated capacity during peak currents to no generation during slack water. Some localized benefits of spatial diversity (in an array of devices) exist similar to those with wave energy, but the water flow and resulting array output power is highly predictable.

As the largest integration studies are so data intensive, they have typically focused on limited scenarios of the more mature renewable resources, wind and solar. Solar tends to dominate variability challenges for the grid, while wind tends to dominate uncertainty challenges. Phase 2 of the Western Wind and Solar Integration Study determined that scenarios with higher penetrations of wind led to higher reserve requirements than those with high penetrations of solar, because reserve requirements for wind and solar are driven by short term uncertainty [19]. One study also found wind is less variable than solar at individual sites, and wind in the study region benefits slightly less from geographic diversity than solar [14]. However, the variability of solar can be somewhat mitigated because much of this variability is the known path of the sun in the sky. Therefore, reserves can be held only in proportion to the clear-sky output [13].

Scheduling time frame affects reserve requirements as well. Areas with hourly scheduling will usually keep all non-regulating resources fixed for the hour, allowing a

ramp to the next hour scheduling. Therefore, a system with hourly scheduling will require more regulating reserves than if it had shorter scheduling intervals [1].

A key conclusion of the more recent studies is that operating reserve requirements need to be dynamic, with an understanding of when the system is at high or low risk used in the scheduling of operating reserves. In addition, longer range forecasts will have higher levels of uncertainty than short range forecasts [1]. Power system operators must focus on managing the net variability of aggregated load and generation, not the variability of individual plants [13]. Aggregation over a mix of geographically diverse renewable sources provides the opportunity to handle the additional variability and uncertainty of these resources more efficiently.

II. METHODS

A. Data Collection/Generation

The various raw data sets are available for different time intervals. Since ten minute intervals are used to calculate following reserve requirements, this was selected as the standard time interval for this study. Load data for 2013 and 2014 was downloaded directly from the BPA website [21] and averaged to ten minute intervals.

Wind power data for 2014 was obtained from two different sources. Wind power generation data (for existing wind plants, primarily in the Columbia Gorge) was obtained from the BPA website [21] and averaged to ten minute intervals. Wind speed data was obtained from two additional locations: Mary's Peak in Oregon, and Sunnyside in Washington [22]. These two locations were selected to provide good geographic diversity from the generation already present in the Columbia Gorge. Using an assumed wind turbine design (Vestas V90), power generation (P) was calculated for the additional locations using (1), where A is the swept area, ρ is the density of air, and V is the wind velocity averaged to 10 minute intervals.

$$P = \frac{1}{2} * A * \rho * V^3 \quad (1)$$

The solar power generation data was developed from 2014 irradiance data downloaded from the University of Oregon Solar Radiation Monitoring Laboratory [23]. Three locations in the Pacific Northwest were used: Aberdeen, Portland and Ashland. Since a few data points were missing, the solar data was arranged in an array, and missing data points were filled in with the previous value, verifying that the resulting data was realistic. The data was then averaged to ten minute increments. Since PV power generation is directly proportional to irradiance, the solar power generation is scaled as

needed for different scenarios, and efficiency losses in PV power generation will be lost upon scaling, the downloaded irradiance data was used directly.

Data from measurement buoys deployed near Newport, Oregon, were used to model wave power generation data. Data from two deployments are available, one summer (July 30 to September 27, 2013) and one winter (November 9, 2014 to January 23, 2015). A Markov Chain was constructed for each set and used to generate year-long wave power generation data (in 10 minute increments) for both winter and summer sea states. More information on the technique is available in [24]. The winter data is then used for the winter months of December, January, and February, while summer data is used for June, July, and August. The data is combined to ramp from summer to winter at 25% per month in the fall, and to ramp from winter to summer at 25% per month in the spring, providing a full year of seasonal wave power data. Since wave power is generated from measurement buoy data, two additional data sets were generated in a similar manner, creating a total of three simulated sites.

Since tidal power generation potential is not weather dependent, an existing set of tidal data from 2011 was used. This data was previously downloaded from the University of Washington Northwest National Marine Renewable Energy Center [25]. Separate data sets contained velocity information of the tides in one-minute increments at 1m above the sea bed. The data sets were combined and gaps in the information were filled in using preceding values; the data was then averaged to ten minute intervals. The velocity data was converted to power using (1), where A is the turbine swept area (assumed to be 1), ρ is the density of water, and V is the tidal velocity. Unlike wind, there are no widely used commercial tidal turbines. Scaling the tidal power data for various scenarios means the

turbine swept area and the efficiency losses scale linearly, negating the need to determine their specific values.

B. Data Analysis

In order to focus on the impact of renewable mix and geographic diversity on the reserve requirements, a set renewable penetration of 36% was used. This number was selected to be slightly higher than the applicable renewable portfolio standards, and also because it is easily divisible into the different combinations to be analyzed. These combinations of renewable sources are listed in Table 1.

TABLE 1
RENEWABLE SOURCE PENETRATIONS (%)

<i>Test #</i>	<i>Wind 1</i>	<i>Wind 2</i>	<i>Wind 3</i>	<i>Solar 1</i>	<i>Solar 2</i>	<i>Solar 3</i>	<i>Wave 1</i>	<i>Wave 2</i>	<i>Wave 3</i>	<i>Tidal</i>
1										
2	36									
3	12	12	12							
4				36						
5				12	12	12				
6							36			
7							12	12	12	
8	18			18						
9	18			6	6	6				
10	6	6	6	6	6	6				
11	18						18			
12	18						6	6	6	
13	6	6	6				6	6	6	
14	12			12			12			
15	4	4	4	4	4	4	4	4	4	
16	9			9			9			9
17	3	3	3	3	3	3	3	3	3	9
18	12			12			9			3
19	4	4	4	4	4	4	3	3	3	3

Wind 1 – Columbia Gorge, Wind 2 – Mary’s Peak, Wind 3 – Sunnyside
Solar 1 – Portland, Solar 2 – Aberdeen, Solar 3 – Ashland

The different combinations of renewable sources were analyzed using Matlab. The data sets were loaded into variables, and the renewable power generation sets were scaled to the needed penetration levels listed in Table 1 (scaling the peak of each renewable source relative to the peak load). The load and renewable energy schedules were then generated utilizing the one-hour persistence method. This method states that the power output for the next hour will be the same as when the prediction is made. Predictions are made at the 40-minute mark of the hour, and the prediction will be good for the 10-minute through the 50-minute mark of the next hour, with 20 minutes allowed to ramp between predictions [24].

Once the time-series schedules for load and renewable energy sources were created, the renewable energy schedules were subtracted from the load schedule to create a net load schedule. The following and imbalance reserve requirements were then determined for each ten minute interval. The top and bottom 0.25% (0.5% total) of the following and imbalance arrays were discarded as per industry standard practice. This allows utilities to meet reliability standards while eliminating events beyond three standard deviations of the following and imbalance mean [24]. After the data trimming, the following and imbalance maximum and minimum, plus other statistical measures, were listed for each test scenario.

III. RESULTS

The trimmed maximum and minimum reserve requirements for each of the scenarios are shown graphically in Figure 1 (Following) and Figure 2 (Imbalance). In each graph, Test 1 is the baseline of no renewable generation. For reference, 0.01pu is approximately 100MW.

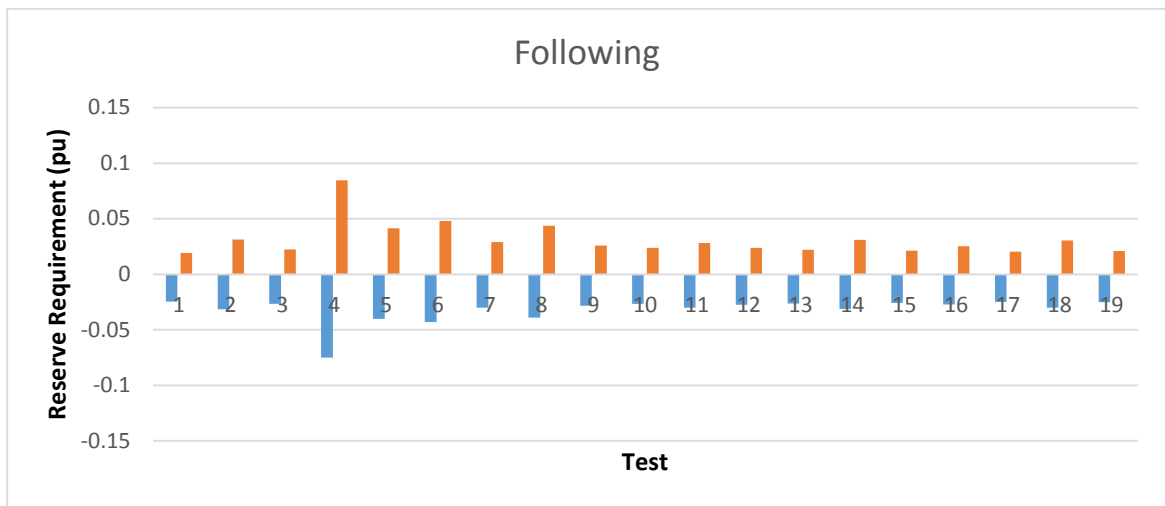


Figure 1. Following reserve requirements

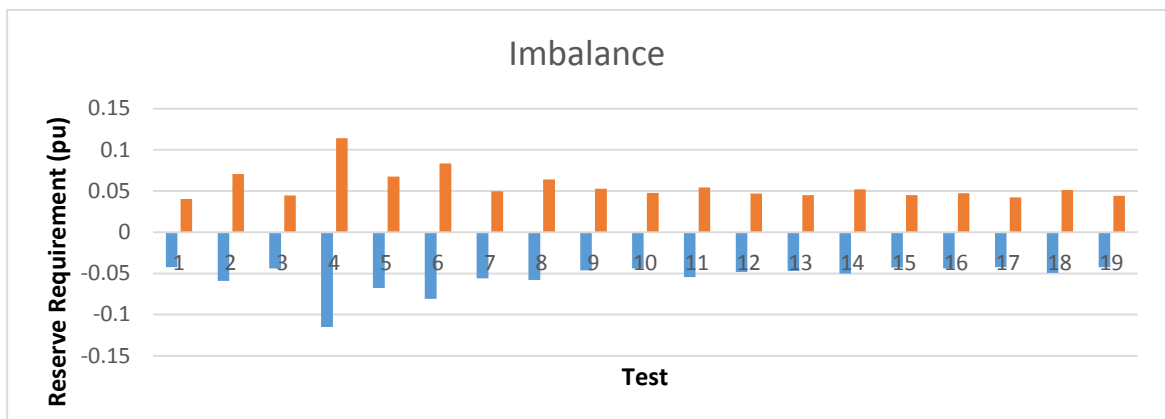


Figure 2. Imbalance reserve requirements

The numerical values, including statistical analysis, are shown for selected options in Table II. These options were selected based on Figure 1 and Figure 2 to

represent a range of renewable sources. The percentage of the penetrations are shown in Table 1, with Test 1 no renewables, Test 2 concentrated wind, Test 3 diverse wind, Test 10 diverse wind and solar, Test 15 diverse wind, solar and wave, and Test 19 diverse wind, solar, wave and tidal.

The variance is defined as the square of the standard deviation. Skew is a measure of the asymmetry of the following and imbalance distributions, while kurtosis defines the “peakedness”; a normal distribution has a kurtosis of 3. Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are both measures of forecast error.

TABLE II
TRIMMED FOLLOWING AND IMBALANCE RESERVE REQUIREMENTS
FOR SELECTED OPTIONS

	<i>Test #</i>						
	<u>1</u>	<u>2</u>	<u>3</u>	<u>10</u>	<u>15</u>	<u>19</u>	
Following	Minimum	-0.0247	-0.0316	-0.0265	-0.0265	-0.0257	-0.0253
	Maximum	0.0192	0.0314	0.0224	0.0238	0.0212	0.0209
	Mean	1.37E-05	-1.8E-06	5.97E-06	2.31E-06	1.02E-05	1.07E-05
	Variance	2.88E-05	5.51E-05	3.62E-05	4.67E-05	4.01E-05	3.88E-05
	Skew	-0.235	-0.087	-0.189	-0.114	-0.097	-0.113
	Kurtosis	5.15	4.98	4.88	4.16	4.16	4.19
	MAE	0.00384	0.00534	0.00425	0.00506	0.00471	0.00463
	RMSE	0.00537	0.00742	0.00602	0.00684	0.00633	0.00623
Imbalance	Minimum	-0.0425	-0.0590	-0.0441	-0.0439	-0.0426	-0.0424
	Maximum	0.0403	0.0708	0.0447	0.0479	0.0450	0.0443
	Mean	-1.8E-06	-2.9E-06	-1.3E-05	-1.6E-05	-1.2E-05	-1.1E-05
	Variance	9.35E-05	3.06E-04	1.31E-04	1.84E-04	1.44E-04	1.4E-04
	Skew	-0.166	0.204	-0.010	0.184	0.149	0.158
	Kurtosis	5.08	4.23	4.29	3.53	3.74	3.77
	MAE	0.00705	0.0129	0.00858	0.0104	0.00920	0.00905
	RMSE	0.00967	0.0175	0.0115	0.0136	0.0120	0.0118

IV. DISCUSSION

It is apparent from Figure 1 and Figure 2 that significant penetrations of solar increase the reserve requirements. The one-hour persistence method of forecasting used in this study may have affected the results, as basing the forecast on the predictable clear-sky output has been suggested as a preferred method [13].

Comparison of the scenarios in Figure 1 and Figure 2 show that each pair of concentrated vs. geographically diverse renewables (e.g., Test 2 with concentrated wind and Test 3 with diverse wind) has lower reserve requirements for the diverse scenario. This conclusion matches those of many prior studies. While the total penetration is nowhere near the level in this study, Test 2 most closely represents the current situation and trend in the Pacific Northwest, with wind resources concentrated in the Columbia Gorge.

It is also interesting to look at other groups of scenarios. Tests 8, 9 and 10 show the impact of increasing geographic diversity on the combination of wind and solar. Tests 11, 12 and 13 are a similar set of combinations for wind and wave. In both of these groups, the benefit of increased geographic diversity is evident. Further, the pairs of Test 14 and 15, Test 16 and 17, and Test 18 and 19 show the advantage of geographic diversity still exists when three or four types of renewable sources are used.

In order to keep the scenarios realistic for the area, wind sources are present in most. Although the significant use of a highly predictable source such as tidal would have minimal impact on reserve requirements, this is not a feasible option to consider. In Figure 1 and Figure 2, the number of sources and extent of geographic diversity increase

toward the right side of the graphs, and the resulting trend of decreased reserve requirements is apparent.

In a perfect (but totally unrealistic) scenario, the mean, variance and skew of the reserve requirements would all be zero. At the same time, the kurtosis would be extremely large. This combination of statistics would indicate that no reserve requirements were necessary. As the reserve requirements move away from the ideal, utilities must plan for the minimum and maximum reserve requirements. Therefore, it is better to have a smaller minimum and maximum with lower kurtosis, than a larger minimum and maximum with higher kurtosis. This distinction can be seen in Table II when comparing Test 2, concentrated wind, with the more diverse combinations of Tests 3, 19, 15 and 19. Based on the minimum and maximum values, Test 19 with geographically diverse wind, solar, wave and tidal has the lowest reserve requirements.

V. CONCLUSIONS AND FUTURE WORK

The results of this study show that increasing the mix and geographic diversity of renewable sources decreases the reserve requirements.

Future work can incorporate several different enhancements. First, unique methods of forecasting each renewable resource can be incorporated, to utilize the optimal method for each. It may also be desirable to follow the current industry trend of reducing the forecasting and scheduling interval. In addition, more geographically diverse sites for each renewable resource can be included.

The analysis could be restructured as an optimization problem, to determine the mix of geographically diverse sources to minimize the reserve requirements. Constraints can be defined to maintain existing sites as given, and expected efficiencies of potential geographic locations could be addressed. It may be possible to further extend the work to include basic economic factors (initial costs plus unit generation costs), as well as the cost and potential benefits of energy storage.

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