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A Solar Reserve Methodology for Renewable Energy Integration Studies Based on Sub-Hourly Variability Analysis

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***Abstract*—Increasing penetrations of wind and solar energy are raising concerns among electric system operators because of the variability and uncertainty associated with the power sources. Previous work focused on the quantification of reserves for systems with wind power. This paper presents a new methodology that allows the determination of necessary reserves for high penetrations of photovoltaic power and compares it to the wind-based methodology. The solar reserve methodology was applied to Phase 2 of the Western Wind and Solar Integration Study. A summary of the results is included.**

***Keywords*—photovoltaic, power system operations, reserves, solar power, wind power**

I. NOMENCLATURE

- P: actual power generated
- P_{CS}: clear-sky power, or hypothetical power generated in the absence of clouds
- P_F: power forecast
- SPI: solar power index, which is the ratio P/P_{CS}
- ΔP: difference in power output between two time steps
- Δt: time step

II. INTRODUCTION

One of the main concerns with the integration of high penetrations of wind and solar generation is the effect their variable nature can have on the system. To hedge against this variability, system operators can hold additional reserves so that the system can economically respond to unexpected events. A reserve methodology was developed for wind power in the Eastern Wind Integration and Transmission Study (EWITS) [1], but currently a counterpart does not exist for solar power.

The objective of this paper is to analyze sub-hourly photovoltaic (PV) data series, which have been recently synthesized based on observed measurements and satellite imagery [2]. Based on this analysis, a robust (yet simple to implement) reserves methodology was created to inform the commitment and economic dispatch of electrical systems with high penetrations of solar data. Unlike wind, PV power has a predictable daily component (represented by the clear-sky output) that adds complexity to the problem. Our methodology is able to successfully extract this component and minimize the need for reserves, which leads to lower production costs. This method is also able to capture variations in daily and seasonal trends.

The methodology was applied to the Western Wind and Solar Integration Study Phase 2 (WWSIS2) [3]. This study presents scenarios with high penetrations of renewable energy. In particular, the high-solar scenario considered 25% of solar penetration and 8% of wind in the Western Interconnection (WI). The operation of each scenario was modeled using PLEXOS and the reserve methodology was subsequently validated through the 5-min dispatch in [4].

The remainder of this paper is organized as follows: Section III introduces the concept of operating reserves and the wind reserve methodology; Section IV introduces WWSIS2; Section V presents the new solar reserve methodology, along with its validation; and Section VI concludes.

III. RESERVES AND WIND POWER

A. Operating Reserves

Operations of power systems occur at a range of time scales that can be summarized, from longer to shorter, as shown in Fig. 1 [5]. *Unit commitment* and *scheduling* are performed over days to economically commit the units in the system to meet forecasted load and other system requirements. During shorter periods of time (minutes to hours), the system re-dispatches its units to counteract deviations from the schedule through *load following*. Similarly, traditional units are re-dispatched to perform *regulation*, which is the fast response of generators to changes that range from seconds to minutes.

Through these steps, the power system operator is able to maximize the use of cheap base load units (e.g., nuclear or coal-fired generators) while utilizing fast-response units (e.g., natural gas combustion turbines) to maintain system stability and reliability.

Operating reserves are required by the operator so the system can positively respond to forecast errors and events that cannot

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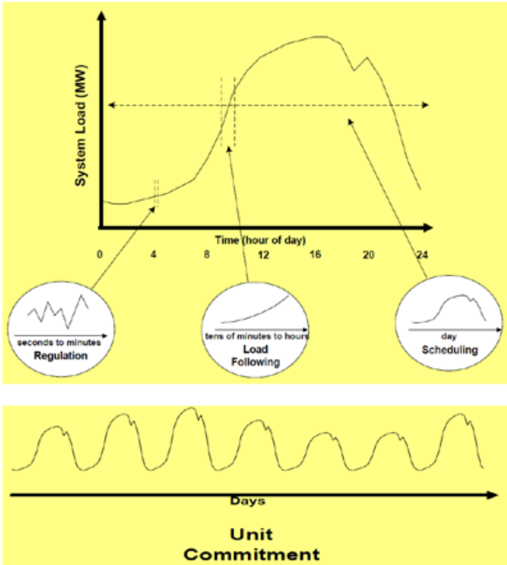

Figure 1 Power system time scales

be accounted for in the scheduling process. In the United States, the most common are regulation reserves, although load following, or *flexible*, reserves are becoming more popular. Both are designed to account for the system's variability (random but expected changes in the system) and uncertainty (unexpected changes). Both load and conventional generators affect the variability and uncertainty through forecast errors and unexpected outages, respectively.

Nonconventional renewable generation, such as wind and PV solar, are variable and uncertain in nature because their output depends on ever-changing wind speeds and solar irradiance that cannot be completely predicted ahead of time. Thus, high penetrations of these resources lead to an increase in reserves necessary in the system. These requirements are especially critical in long-term integration studies, such as EWITS or the Western Wind and Solar Integration Study, which simulate higher renewable energy penetrations than in today's systems.

B. *Wind Reserve Methodology*

Previous work [3, 5] has been able to quantify the uncertainty of wind power. Because short-term variations in wind power output are hard to predict, persistence forecasts are used to calculate uncertainty. For instance, for an economic dispatch model run in 5-min intervals, 10-min-ahead forecasts would be used. The forecast errors can be calculated by comparing the forecasted and the actual power output.

Fig. 2 shows forecast errors represented against the actual power output. The plot corresponds to the entire WI footprint for the high-solar scenario for WWSIS2, which is introduced in more detail in the following section. The general trend that can be observed is that forecast error variability is highest around the 50% production level. It is expected that changes can go up and down and also that the turbine power conversion is the steepest at that point.

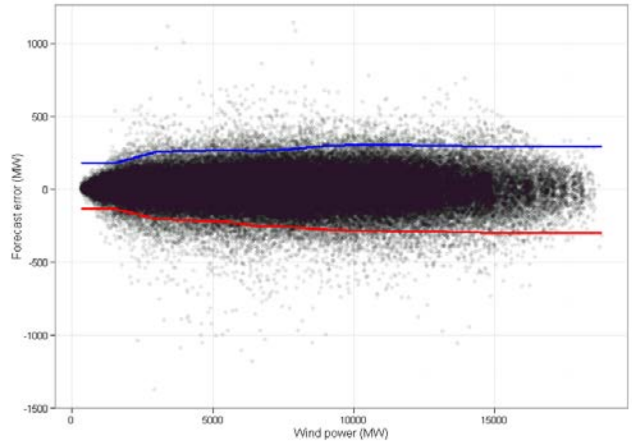

Figure 2. Wind 10-min forecast errors versus power output, along with 95% confidence interval bands

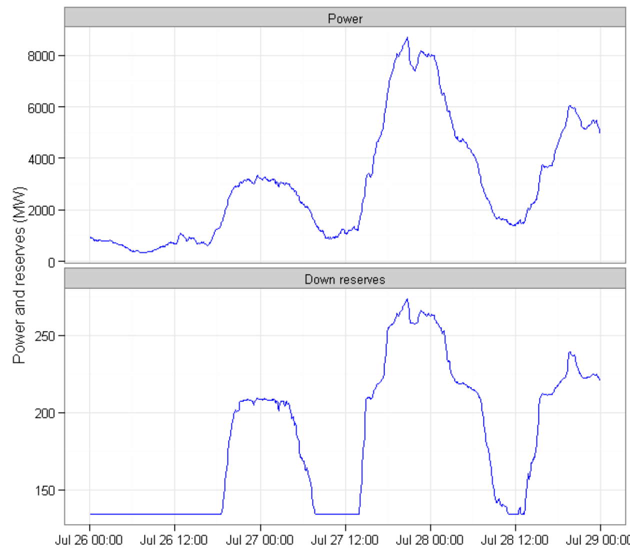

Figure 3. Wind power production and dynamic reserve requirements for the WI

Confidence intervals (represented as red and blue lines) were used to determine up and down reserve requirements so that a certain percentage of occurrences were covered by the reserves. In Fig. 2, the confidence intervals covered 95% of forecast errors. The result was a dynamic determination of reserve requirements, as represented in Fig. 3. Similar plots and time series can be produced for other time steps, such as 30 min or 1 hour, to calculate flexibility reserve requirements.

IV. Phase 2 of the Western Wind and Solar Integration Study

The solar reserve methodology in this paper has been developed based on data from WWSIS2. WWSIS2 examined three scenarios with 33% energy penetration of renewables and a reference scenario for the WI. The reference scenario and conventional generation fleet were consistent with other studies performed by the Western Electricity Coordinating Council's Transmission Expansion Planning Policy Committee [6].

Table I summarizes the breakdown of variable generation between wind and solar for these scenarios. Although the reference and high-solar scenarios had the same wind penetration, the location of wind generators to achieve the 8% energy penetration varied slightly, leading to slightly different amounts of installed capacity. Although solar refers to both PV and concentrated solar power (CSP), only PV was considered in this analysis. The reason is that in Phase 1 of the Western Wind and Solar Integration Study, CSP presented several hours of storage; thus, it can be dispatched to a certain degree.

TABLE I. BREAKDOWN OF WWSIS2 SCENARIOS

Scenario	Wind Penetration	Solar Penetration	Wind Capacity (GW)	Solar Capacity (GW)
Reference	8%	3%	27.9	11.4
High Wind	25%	8%	66.2	34.6
High Mix	16.5%	16.5%	43.8	54.9
High Solar	8%	25%	23.4	81.7

Load time series data from 2006 was chosen from the Ventyx Velocity Suite [6] and was increased to represent the load in 2020, the focus year. The wind data set was derived from the large wind speed and power database [7] developed by 3TIER using a Numerical Weather Prediction model applied to the West. Because the model allows for the re-creation of the weather at any time and space, wind speed data was sampled at representative hub heights for modern wind turbines every 10 min for a 3-yr period on a 2-km spatial resolution. The resulting data set was then used to construct the 2006 time series, which was paired with the 2006 load data time series to preserve the consistency of common weather impacts. Solar data was produced by the National Renewable Energy Laboratory [9] based on the satellite-derived irradiance generated by the State University of New York/Clean Power Research [10], which is available on a 10-km grid at an hourly resolution. Sub-hourly data were interpolated as described in [2].

V. SOLAR RESERVE METHODOLOGY

The proposed solar reserve methodology builds upon the wind methods previously presented. Some adjustments were necessary to take into account solar daily patterns that occur, but the process followed three distinct steps: (a) definition of forecast error; (b) use of explanatory variables to group similar patterns; and (c) application of the reserve requirements based on the explanatory variables.

With this formalized framework in mind, the wind forecast errors were calculated based on persistence forecasts. Power output was used as an explanatory variable to find reserve requirements (Fig. 3) and to create the dynamic reserve requirements (Fig. 4). The following subsections develop similar concepts for PV power.

A. Solar Forecast Errors

Solar-based generation presents clear patterns because of its dependency on the sun. These patterns are best captured with clear-sky simulations, which calculate the power output in the absence of clouds. The top panel in Fig. 4 represents the actual and clear-sky power outputs in the WI during three summer days in the high-solar scenario. The bottom panel in Fig. 4 represents the 10-min ramps in the same time scale.

If the same power-persistence forecast used for wind was applied in this case, we would have consistently seen the largest demand for reserves occurring around sunrise and sunset. However, it is clear from the graph that the power deltas could be decomposed into the contribution from the clear-sky power and a smaller, high-frequency variation. In other words, if the clear-sky trends were removed from the power deltas, the reserve requirements would be smaller.

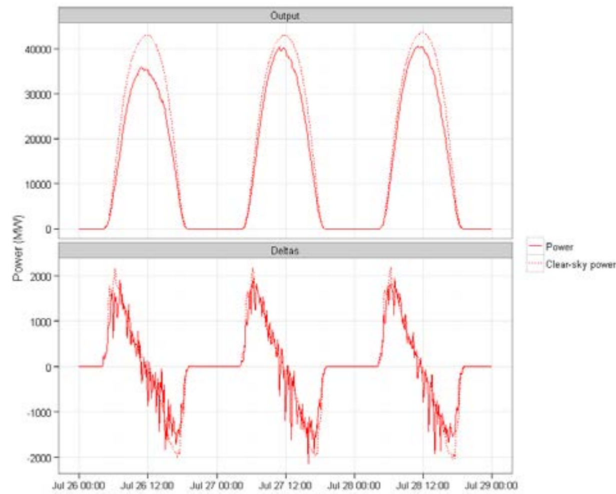

Figure 4. Power and clear-sky power output and ramps

The first step in the creation of the short-term solar forecast was the definition of the *solar power index* (SPI), which represents the ratio between actual power, P, and clear-sky power, P_{CS}. The index can take values between 0 and 1, as shown in (1), and is undefined when P_{CS} is 0.

$$SPI = \min (P/P_{CS}, 1) \tag{1}$$

With this index, we defined the power forecast, P_F, for a time step Δt that utilized known quantities at time t, plus the expected clear-sky power output, which could be pre-calculated for any time of the year based on the location of the sun:

$$P_F(t+\Delta t) = P(t) + SPI(t) \times [P_{CS}(t+\Delta t) - P_{CS}(t)] \tag{2}$$

Graphically, (2) can be represented as shown in Fig. 5. The forecast was based on the persistence of SPI. Thus, to obtain the forecast, we added the clear-sky ramp scaled by the SPI to the current power output. The forecast error could then be calculated:

$$Error = \Delta P(t) - P(t) + SPI(t) \times \Delta P_{CS}(t)] \tag{3}$$

B. Explanatory Variables

The challenge of determining suitable explanatory variables was finding the balance between the overall minimization of reserve requirements and simplicity. We found that the following two variables were especially effective at fulfilling this goal:

- SPI, as defined in the previous subsection, which effectively separated “cloudy” and “sunny” days
- Clear-sky ramps, which separated the different times of the day (positive in the morning, close to 0 at midday, and negative toward sunset)

For WWSIS2, the reserves were calculated based on 5-min time series. The first step was to create ten divisions; subsequently, 100 groups were formed by the combination of both variables. For each group, reserves were calculated by taking the appropriate percentiles (e.g., 2.5% and 97.5% to create 95% confidence intervals). To avoid the reserves being dominated by outliers, reserves were not calculated for a group if it presented less than 20 members. In that case, the reserves for the closest group were used instead.

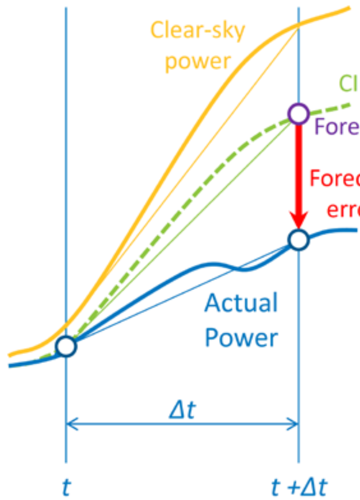

Figure 5. Graphical representation of short-term forecast for solar

This method was applied to all scenarios in WWSIS2. The regulation reserves were calculated using 10-min time and 95% confidence intervals for the entire footprint. The results are represented in Fig. 6. Flexibility reserves were calculated for different subregions using hourly time steps and 70% confidence intervals. Fig. 7 shows the down ramp requirements for Southern California Edison (SCE), the region with the highest PV penetration.

Both figures suggest that reserve requirements depend on the combination of both variables. The highest down reserves requirements were usually located on the top right corner, which corresponded to sunrises where SPI was close to 1. In such occasions, the calculation of SPI was highly unstable given that the denominator in (1) was very small. At times, the forecast called for a "sunny" sunrise, and the clear-sky correction was heavily weighted in (2). The inability to produce a good forecast at these particular instances created the high reserve requirements. The graphs also show that reserves were higher in the middle of days (clear-sky ramps close to 0) that were partly cloudy (SPI around 50%). For particularly sunny days (SPI close to 1), requirements were much smaller.

C. Application of Reserve Requirements

After the reserve requirements were determined, they could be applied to the time series by finding the combination of the explanatory variables that best fit each point in time. Fig. 8 and 9 represent the resulting requirements for regulation reserves in the WI and flexibility reserves in SCE, respectively.

Most of the time, regulation reserves for the high-penetration scenarios stayed below 1% of the nameplate capacity; whereas the reference case could reach 1.5%, as shown in Fig. 10. This reflects the increasing geographical diversity across the interconnections.

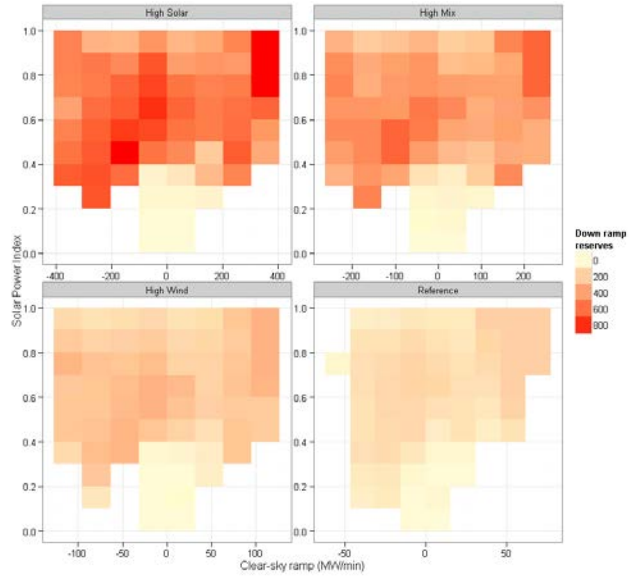

Figure 6. Regulation reserve requirements by scenario for the entire WI

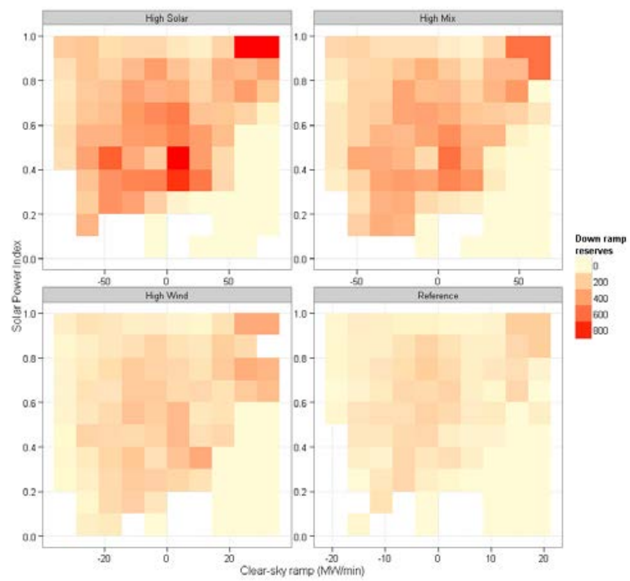

Figure 7. Flexibility requirements by scenario for SCE

Flexibility reserve distributions for SCE were relatively constant across scenarios (Fig. 11).

D. Validation

A 5-min dispatch of the WI using PLEXOS was performed in [4] to test the methodology presented here. A much simpler method can be done to check how often the forecast errors violate the reserve requirements.

First, the 5-min regulation requirements were compared to the forecast errors; the results are summarized in Table II. Overall, the confidence intervals were well maintained. Interestingly, the down-ramp violations were generally more frequent than the up-ramp violations. Table III summarizes the results for flexibility reserve violations in SCE and showed the same trends.

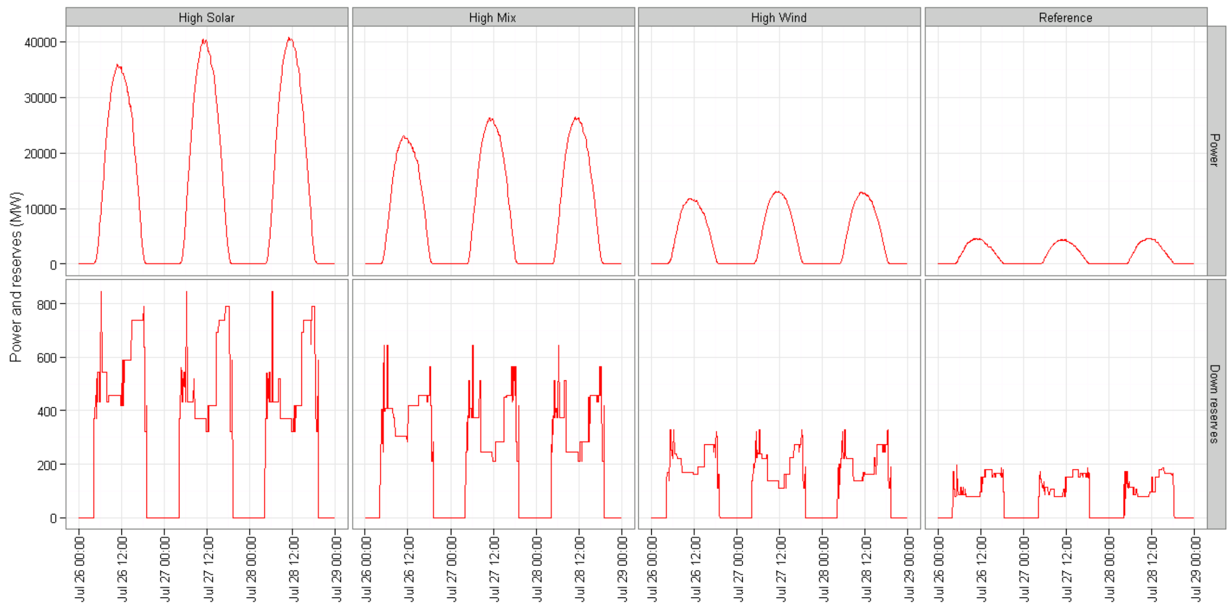

Figure 8. Dynamic regulation reserve requirements for the WI by scenario

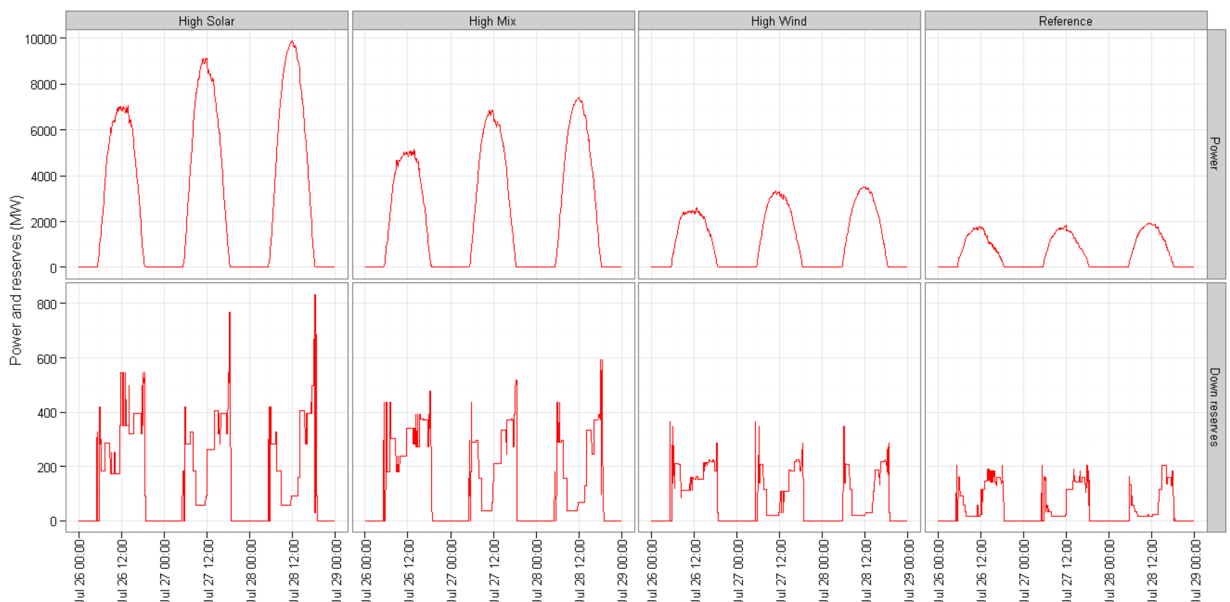

Figure 9. Flexibility reserves for SCE by scenario

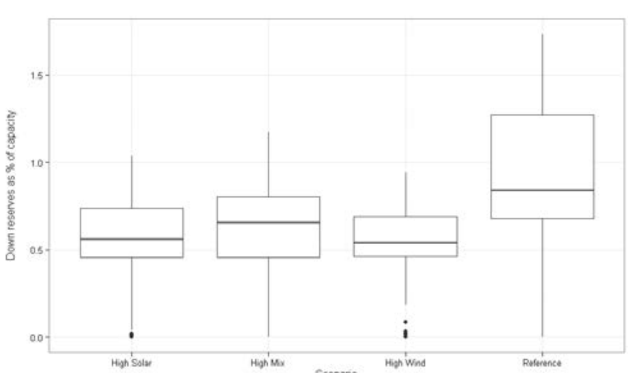

Figure 10. Distribution of regulation down reserves relative to installed capacity for the WI

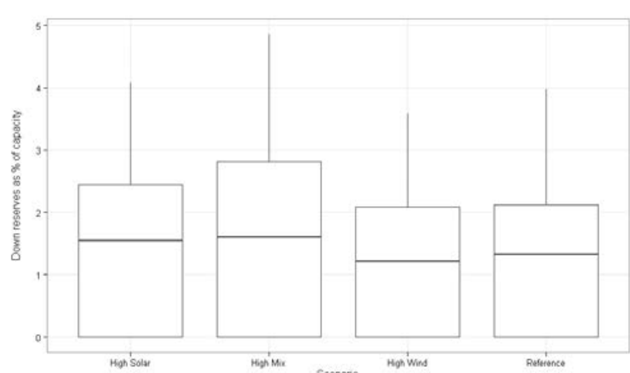

Figure 11. Distribution of flexibility down reserves relative to installed capacity for the WI

TABLE II. FREQUENCY OF REGULATION RESERVE VIOLATIONS

Scenario	Up (%)	Down (%)	Both (%)
Reference	2.6	2.7	5.3
High Wind	1.9	3.2	5.1
High Mix	1.8	3.3	5.1
High Solar	1.9	3.4	5.2

TABLE III. FREQUENCY OF FLEXIBILITY RESERVE VIOLATIONS IN SCE

Scenario	Up (%)	Down (%)	Both (%)
Reference	13.1	18.2	31.2
High Wind	11.6	17.8	29.4
High Mix	11.9	16.8	28.8
High Solar	12.0	16.4	28.4

These statistics were calculated for the hours in which there is potential solar production. If hours of darkness were included, the percentage of violations would drop to 3.2% and 14.8% on average for regulation and flexibility reserves, respectively.

VI. CONCLUSIONS

This paper presented a new methodology for the estimation of solar reserves. It generalized a previous method for wind power reserves. The method includes the determination of a short-term solar forecast based on the solar power index and the use of two explanatory variables, which reduce overall reserve requirements. The method was applied to the scenarios considered in WWSIS2, and graphical representations were included. Finally, the frequency of violations was checked to successfully validate the reserves created.

ACKNOWLEDGMENT

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