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Comparing Resource Adequacy Metrics

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Abstract—**As the penetration of variable generation (wind and solar) increases around the world, there is an accompanying growing interest and importance in accurately assessing the contribution that these resources can make toward planning reserve. This contribution, also known as the capacity credit or capacity value of the resource, is best quantified by using a probabilistic measure of overall resource adequacy. In recognizing the variable nature of these renewable resources, there has been interest in exploring the use of reliability metrics other than loss of load expectation. In this paper, we undertake some comparisons using data from the Western Electricity Coordinating Council in the western United States.**

Keywords-capacity planning; power system reliability; probability; solar energy; wind energy

I. Introduction

As the utilization of wind and solar energy increases around the world, there is an accompanying growing interest and importance in accurately assessing the contribution that these resources can make toward planning reserve. This contribution, also known as the capacity credit or capacity value of the resource, is best quantified by using a probabilistic measure of overall resource adequacy. In recent years, this framework has been recommended by an IEEE task force [1], the North American Electric Reliability Corporation [2], and the International Energy Agency Task 25 on large-scale wind integration [3].

In recognizing the variable nature of these renewable resources, there has been interest in exploring the use of reliability metrics other than loss of load expectation (LOLE), which has historically been calculated on a daily basis. In this paper, we undertake some comparisons using data from the Western Electricity Coordinating Council (WECC) in the western United States.

The remainder of this paper is organized as follows: Section II reviews resource adequacy concepts and metrics, Section III presents the methodology utilized in this analysis, Section IV presents the numerical example, Section V summarizes results, and Section VI concludes.

II. Resource Adequacy and Metrics

Because designing and building a power plant is a time-consuming process, power system planners typically assess the future demand for electricity and then perform a series of analyses to determine how much and what type of generation will be needed at one or more future dates.

Although approaches may vary somewhat, using a measure of resource adequacy, typically based on loss of load probability (LOLP) or a related metric, is a common approach. To determine whether resource adequacy will be achieved, a target reliability level is used. It is common in the industry to use a LOLE level of 1 day in 10 years.

The historical calculation of LOLP was done once per day, using the peak hour. The calculation utilizes a direct convolution of each generator capacity and forced outage rate. Thus, the probability is calculated directly. The LOLE can be calculated as

$$LOLE = \sum_{i=1}^{N} P[C_i < L_i] \quad (1)$$

where *P()* denotes the probability function, *N* is the number of days in a year, C_i is the available capacity from the convolution process, and L_i is the daily peak demand.

To calculate the system LOLE after adding a new generator, the process is repeated:

$$LOLE' = \sum_{i=1}^{N} P[(C_i + g_i) < L_i] \quad (2)$$

where *LOLE'* is the LOLE with the new generator, which provides g_i MW of capacity. The contribution this new generator makes to resource adequacy is its capacity value, or effective load-carrying capability (ELCC).

$$\sum_{i=1}^{N} P[C_i < L_i] = \sum_{i=1}^{N} P[(C_i + g_i) < L_i] \quad (3)$$

This equation is solved iteratively for the increased demand ΔC_i that can be supplied at the original reliability level. This is the capacity value of the resource, and it represents the increase in load that can be supplied by the new resource, holding system LOLE the same as it was prior to the resource addition [4]. The ELCC calculation is illustrated in Fig. 1.

It is trivial to convert the LOLE calculations from daily LOLE to an hourly calculation. The resulting loss of load hours (LOLH) is calculated by replacing all of the daily values in equations (1)-(3).

Other related reliability metrics can be similarly calculated. For example, expected unserved energy (EUE) is the probabilistic estimate of the energy shortfall that results from resource failure. We note that LOLE (daily) and LOLH capture only the number of events and do not capture either the capacity or energy shortfalls. Because of this, EUE is sometimes preferred as the metric of choice. In carrying out ELCC calculations, any one of these basic reliability metrics can be used.

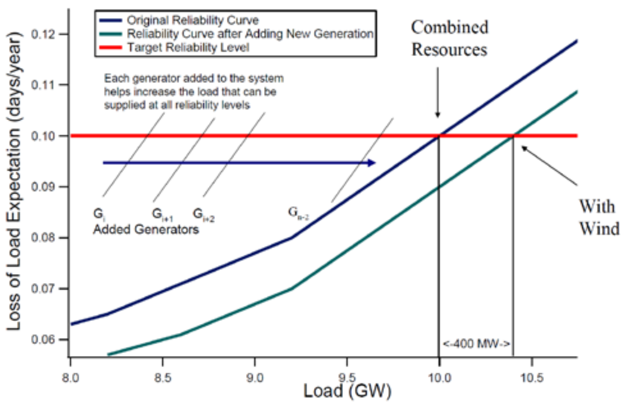

Figure 1. The ELCC of a generator is the horizontal distance between the reliability curves measured at the target reliability level (400 MW at 1 day/10 years).

In reality, the "loss of load" part of the LOLE metrics may not always be accurate in modern interconnected systems. Typically, the LOLE is based on internal generation and demand, possibly including regular imports and exports. In some cases, the calculation may not include rigorous accounting of reserve-sharing groups or other emergency operational measures that allow for neighboring capacity to be used during outage conditions that compromise grid reliability. The impact of transmission on resource adequacy is discussed in [5].

III. The REPRA Model

The Renewable Energy Probabilistic Resource Adequacy (REPRA) tool [6] is being further developed at NREL to better understand how different types of renewable generation, which are usually nondispatchable sources of power, can contribute to a power system's adequacy from a reliability point of view.

At the core of the model resides a fast-convolution algorithm that combines the probability distribution of the traditional generators. These are represented by a finite number of states. The simplest case is whether the unit is available or not, with a probability that it is not equal to the effective forced outage rate (EFOR).

TABLE I. Capacity Outage Probability Table for Conventional Units

MW-OUT	MW-IN	Probability	LOLP
0	300	0.6064	1.0000
50	250	0.3164	0.3936
100	200	0.0688	0.0773
150	150	0.0080	0.0085
200	100	5.20E-04	5.38E-04
250	50	1.81E-05	1.84E-05
300	0	2.62E-07	2.62E-07

After the convolution of the traditional units [7] has been performed, the result is a capacity outage probability table, which indicates the LOLP for all levels of load the system can serve. For example, Table I shows the result when considering six 50-MW units with an EFOR of 8%. The third row shows that the probability of an outage of 100 MW is 0.0688, which is equivalent to the probability of any two units being out of service. Similarly, the cumulative probability of an outage exceeding 100 MW is 0.0773; alternatively, this cumulative probability can be interpreted as the LOLP associated with a 200-MW load level.

Variable generation can be convolved with the capacity outage probability table in a similar fashion. The main difference is the way in which the probability distribution used in the convolution is determined. Unlike traditional generators, VG production is limited by available resources such as wind speed or solar irradiance that are governed by weather patterns. To preserve this variation, we made use of a sliding window technique [8] for all hours of the year. Fig. 2 shows a graphical representation of a sliding window, which included the current and adjacent hours. The width was predetermined and, in this case, included a total of 5 hours. Power outputs in the window were then given equal probability and sorted, providing the necessary probability distribution that would be included in an equivalent outage table (Table II). This table was then convolved with the results in Table I to obtain the total system outage table (Table III). This table was truncated for LOLP values below 0.001.

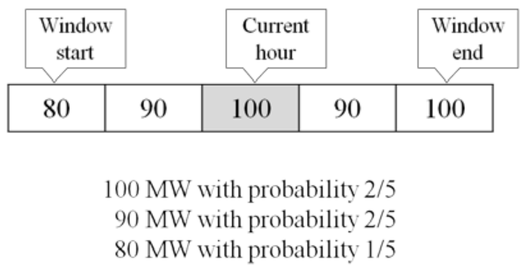

Figure 2. Example of sliding window for wind power generation

TABLE II. Capacity Outage Probability Table for Wind Sliding Window

MW-OUT	MW-IN	Probability	LOLP
0	100	0.4	1.0
10	90	0.4	0.6
20	80	0.2	0.2

REPRA allows for the study of resource adequacy for different levels of geographic aggregation. This will contribute to a better understanding of the contribution of VG and also, as in this case, better determine the benefits of a more interconnected system.

TABLE III. Example of Capacity Outage Probability Table

MW-OUT	MW-IN	Probability	LOLP
0	400	0.243	1.000
10	390	0.243	0.757
20	380	0.121	0.515
50	350	0.127	0.394
60	340	0.127	0.267
70	330	0.0633	0.141
100	300	0.0275	0.077
110	290	0.0275	0.050
120	280	0.0138	0.022
150	250	0.0032	0.008
160	240	0.0032	0.005
170	230	0.0016	0.002

IV. NUMERICAL EXAMPLE

This paper examines the relationships among different reliability metrics and their effects in the calculation of capacity value for wind and solar generation. This analysis is performed based on WECC's Transmission Expansion Planning Policy Committee (TEPPC) 2024 data set [9]. The data is compiled and vetted through WECC processes and is used to examine future transmission scenarios in the Western Interconnection.

The calculations in this paper are performed at the pool and interconnection levels. The definition of the pools in the TEPPC database is presented in Table IV and graphically in Fig. 3. Table IV also includes the planning margins (summer and winter) that TEPPC utilizes to guide the capacity expansion process. The resulting generation mix satisfies these margins, as examined by TEPPC [9].

TABLE IV. DEFINITION OF POOLS IN THE WESTERN INTERCONNECTION

Pool	Includes	Summer Margin	Winter Margin
AZ-NM-NV	Arizona, New Mexico, Southern Nevada	13.6%	14.0%
Basin	Idaho, Northern Nevada, Utah	13.7%	13.7%
Alberta	Alberta	12.6%	13.9%
BC	British Columbia	12.6%	13.9%
CA-North	Northern California, San Francisco, SMUD	15.0%	12.1%
CA-South	Southern California Edison, San Diego Gas & Electric, LADWP, Imperial Irrigation District	15.2%	11.0%
NWPP	Pacific Northwest, Montana	17.5%	19.2%
RMPA	Colorado, Wyoming	15%	15.9%

The data set was prepared to be used in production-cost simulation tools (specifically GridView); however, for the resource adequacy calculations in this paper, we require only the load and variable generation time series and the list of conventional generators, along with their capacity and EFOR. Table V summarizes the total capacity by generator type for the entire interconnection.

TABLE V. TOTAL CAPACITY BY GENERATOR TYPE

Class	Capacity (GW)
Biomass	4.5
Geothermal	6.0
Small Hydro RPS	1.3
Solar PV	16.1
Solar CSP0	1.7
Solar CSP6	2.4
Wind	38.1
Hydro	69.8
Pumped Storage	5.6
Electricity Storage	1.3
Coal	44.3
Nuclear	7.7
Combined Cycle	139.7
Combustion Turbine	39.7
Other Steam	20.5
Other	7.3
Negative Bus Load	2.7
Dispatchable DSM	4.8
TOTAL	415.9

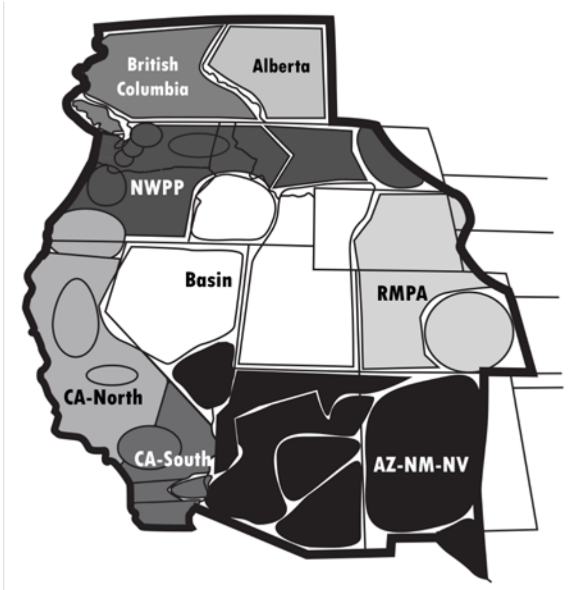

Figure 3. Pools in the Western Interconnection

TABLE VI. RELATIVE CONTRIBUTION TO RESOURCE ADEQUACY BY GENERATOR TYPE AND POOL IN THE TEPPC DATA SET [9]

Generation Type	AZ-NM-NV	Basin	Alberta	BC	CA-North	CA-South	NWPP	RMPA
Biomass RPS	100%	100%	100%	100%	66%	65%	100%	100%
Geothermal	100%	100%	100%	100%	72%	70%	100%	100%
Small Hydro RPS	35%	35%	35%	35%	35%	35%	35%	35%
Solar PV	60%	60%	60%	60%	60%	60%	60%	60%
Solar CSP0	90%	95%	95%	95%	72%	72%	95%	95%
Solar CSP6	95%	95%	95%	95%	100%	100%	95%	95%
Wind	10%	10%	10%	10%	16%	16%	5%	10%
Hydro	70%	70%	90%	90%	70%	95%	70%	70%
Pumped Storage	100%	100%	100%	100%	100%	100%	100%	100%
Coal	100%	100%	100%	100%	100%	100%	100%	100%
Nuclear	100%	100%	100%	100%	100%	100%	100%	100%
Combined Cycle	95%	95%	100%	95%	95%	95%	95%	95%
Combustion Turbine	95%	95%	100%	95%	95%	95%	95%	95%
Other Steam	100%	100%	100%	100%	100%	100%	100%	100%
Other	100%	100%	100%	100%	100%	100%	100%	100%
Negative Bus Load	100%	100%	100%	100%	100%	100%	100%	100%
Dispatchable DSM	100%	100%	100%	100%	100%	100%	100%	100%

During TEPPC's resource adequacy assessment, different generators types in different areas are assigned different relative contributions (Table IV) [9]. For instance, 100% of the capacity from geothermal generators is counted to meet the reserve margins in Table IV, except in the California North and South pools, where the capacity is derated to 72% and 70%, respectively.

The calculations in this paper respected the duration presented in Table VI for all generators, except for wind and solar resources. For those resources, the time series in the data set were used; their calculated capacity values are presented in the next section.

V. RESULTS

A. Reliability Metrics

The first step was evaluating different reliability metrics for the given load levels and resources available. Such calculations revealed that all metrics considered (LOLE, LOLH, EUE) were not significant and could be considered close to zero for all pools. Thus, the reserve margins in Table IV provide reliability levels beyond the typical 1 day in 10 years.

Alternatively, we can calculate the ELCC of the generation mix for that reliability level. The results are summarized in Table VII and include the multiplier that needs to be applied to the load profiles to reach a LOLE of 0.1 day/year. The table also includes the corresponding LOLH and EUE values for each pool, in addition to the maximum LOLP value observed in the year.

TABLE VII. ELCC AND OTHER METRICS BY POOL AT A LOLE LEVEL OF 0.1 DAY/YEAR

Pool	Load mult.	Peak Load (GW)	LOLH (h/y)	EUE (MWh)	Peak LOLP
Alberta	1.44	22.8	0.241	63.5	0.024
AZ-NM-NV	2.05	71.0	0.187	99.6	0.053
Basin	1.44	23.1	0.245	77.4	0.039
BC	1.59	19.5	0.100	6.7	0.040
CA-North	1.77	52.1	0.179	71.5	0.056
CA-South	1.47	63.1	0.144	58.3	0.100
NWPP	1.49	51.0	0.139	50.4	0.057
RMPA	1.73	23.3	0.249	79.0	0.067
Interconnect	1.85	327.3	0.129	112.1	0.078

B. Metric Comparison

The calculations that lead to the results in Table VII can be repeated for different LOLE levels to better understand how the different metrics relate. We perform such calculations for a wide range of LOLE values, between 1 day/year and 1 day/100 years. Twenty intermediate points are evaluated. Fig. 4 plots the results of the dependency between LOLE and LOLH for each pool and the interconnection. As shown, the relationship between the two metrics is largely linear. The slope depends both on the number and size of the generators (smaller areas tend to have larger slopes), as well as the net load shape (profiles that show higher relative peaks tend to have larger slopes) [10].

Figs. 5 through 7 show the relationships among LOLH, EUE, and maximum observed LOLP with respect to LOLE using logarithmic scales. In all cases, the relationships are close to linear.

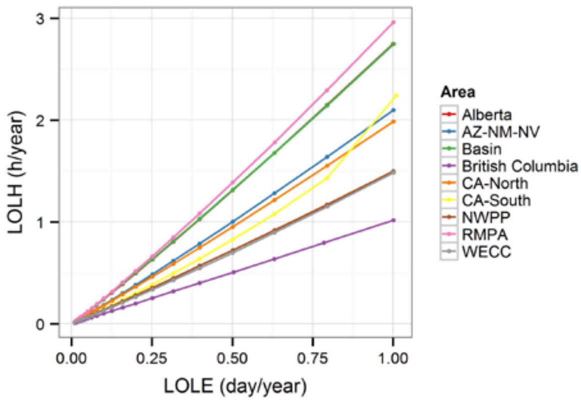

Figure 4. LOLH compared to LOLE using linear scales

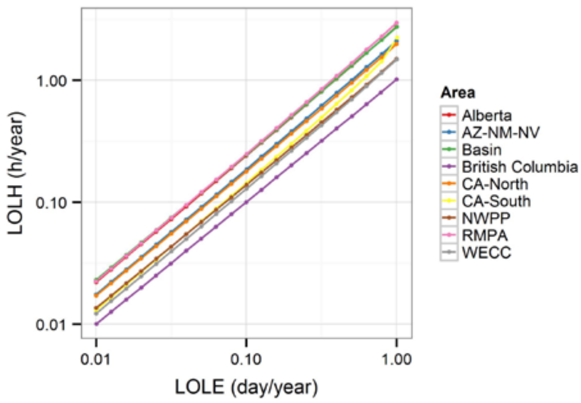

Figure 5. LOLH compared to LOLE using logarithmic scales

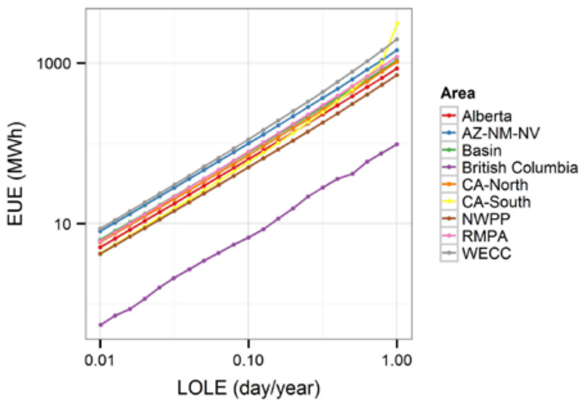

Figure 6. EUE compared to LOLE using logarithmic scales

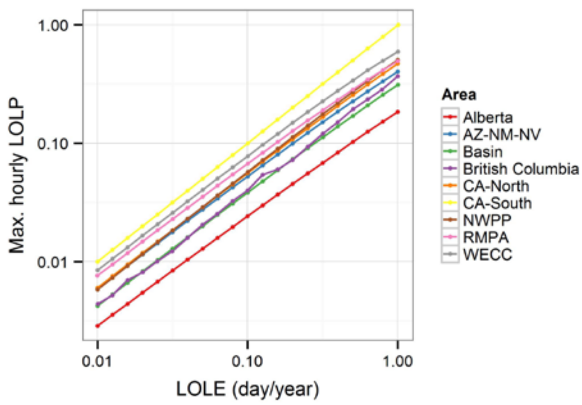

Figure 7. Maximum LOLP compared to LOLE using logarithmic scales

C. Capacity Value Calculations

Capacity values for wind, photovoltaic (PV), and concentrating solar power (CSP) for each pool are then calculated. This value is estimated as the ELCC of each generator type for a given reliability metric and a reliability level. Three metrics are used (LOLE, LOLH and EUE), along with the same wide range of reliability levels (equivalent to LOLE ranging from 1 day/year to 1 day/100 years). The next series of graphs present the results for the three metrics; the horizontal axis represents the LOLE level.

Wind capacity value by pool (and interconnection) is presented in Fig. 8. For the immense majority of cases, the results are identical for all three metrics. The results present small variations with respect to reliability levels. The exception is Southern California for low reliability levels (which also present a nonlinear behavior for that range, as shown in Fig. 4). The capacity values range from 5% to 30% compared to the 5% to 16% ranges considered by TEPPC (Table VI).

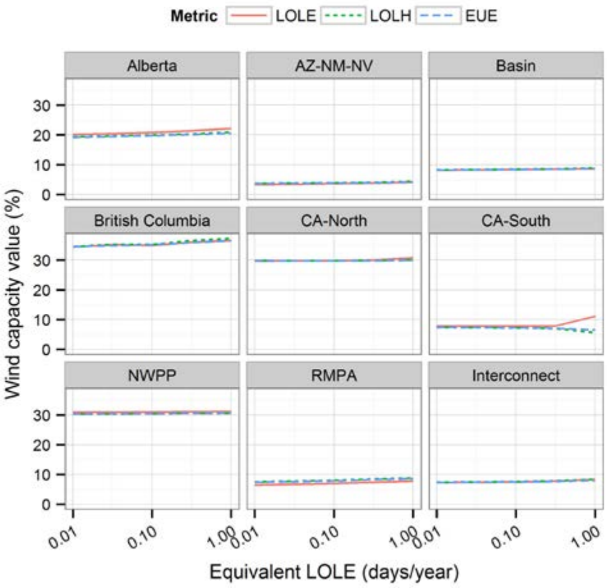

Figure 8. Wind capacity value for different metrics and reliability levels

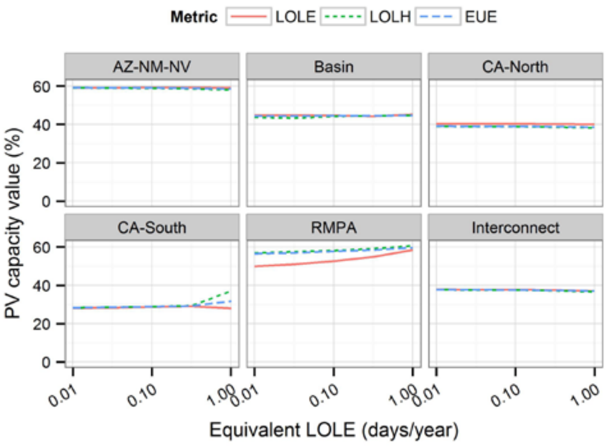

Figure 9. PV capacity value for different metrics and reliability levels

PV capacity values (Fig. 9) are also fairly insensitive to the choice of metric and reliability level. The TEPPC resource adequacy procedure assumed a capacity value of 60% across all polls, which is only achieved in AZ-NM-NV and RMPA. The rest of the pools show capacity values that range from 30% to 45%.

CSP capacity values are calculated using the resource profiles provided by TEPPC; however, these generators typically present some level of storage, which would allow shifting some of this generation toward peak hours that might happen later in the day [11]. This is the reason why these generators are provided a capacity value of 95% to 100% in the TEPPC assumptions. Performing a production-cost simulation was beyond the scope of the study; thus, the resource profiles were used instead.

The resulting capacity values for CSP (Fig. 10) also present small deviations when the metric or the reliability level changes (except for California). Values of 70% to 80% are observed in most pools, which is consistent with the 70% assumption in Table VI for CSP0 (without storage). The exception is California South, which has a value of 30% because of a high concentration of PV and CSP in the pool, which can quickly reduce the capacity value of solar power [12].

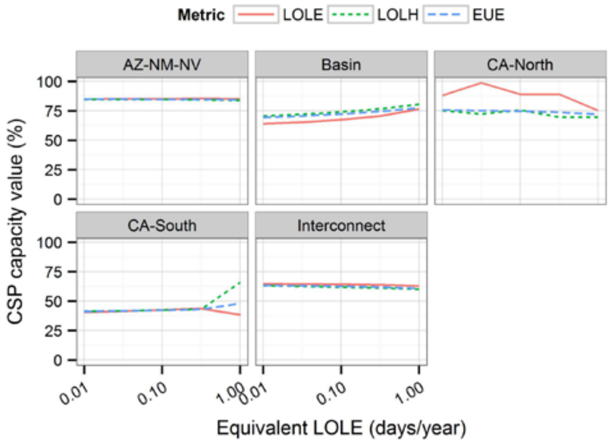

Figure 10. CSP capacity value for different metrics and reliability levels

VI. Conclusions

Estimating resource adequacy levels in the presence of variable generation is currently an open area of research. This paper presented different probability-based metrics for that purpose and utilized a real-world example data set from the U.S. Western Interconnection to systematically compare LOLE, LOLH, EUE, and maximum LOLP. The relationships among these metrics is very close to linear, which indicates high levels of correlation among them, even when evaluated for a broad range of reliability levels. This high correlation means that estimates that are performed with one of the selected metrics are robust relative to the use of the other metrics tested.

These metrics were also used to independently estimate the capacity value of wind, PV, and CSP in the Western Interconnection. The results showed that capacity value, in general, is not very sensitive to the choice of metric or reliability level. We have also shown that the TEPPC estimates of capacity value of wind and PV are not consistent with the more rigorous LOLE-related metrics. For wind power, the LOLE-based approaches result in estimates from 5% to 30% of rated capacity, depending on the region. The TEPPC approach uses 10% of rated capacity. For PV, the LOLE-based methods yield 30% to 45% of rated capacity in most regions. The exception is the AZ-NM-NV region, in which the LOLE-related approaches find approximately a 60% ELCC. In all TEPPC cases 60% is used as the capacity value of PV. These results suggest the possibility that TEPPC cases are slightly underbuilt, based on the LOLE analysis presented here. However, treatment of the impact of transmission interconnection may also have an impact on these results, and should be analyzed in subsequent work.

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