A Probabilistic Approach to Quantifying the Contribution of Variable Generation and Transmission to System Reliability

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A Probabilistic Approach to Quantifying the Contribution of Variable Generation and Transmission to System Reliability

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Abstract—**The increasing electrical load served by variable generation (VG), such as wind and solar energy, in the United States and many other countries has stimulated an interesting line of research to better quantify the capacity value of these resources. Methods applied traditionally to thermal units based on their average outage rates do not apply to VG because of their uncertain and non-dispatchable nature. The North American Electric Reliability Corporation's Integration of Variable Generation Task Force recently released a report that highlighted the need to develop and benchmark underlying loss-of-load expectation and related metrics that reasonably and fairly calculate the contribution to planning reserves, or capacity value, of solar and wind power. As the fraction of generation coming from VG becomes more significant, their estimated capacity value will have a larger impact on system planning. In this paper, we provide a method to include VG in traditional probabilistic-based adequacy methods. This method was implemented in the Renewable Energy Probabilistic Resource Assessment tool, which was developed at the National Renewable Energy Laboratory. Through an example based on the U.S. Western Interconnection, this method was applied to assess the effect that transmission can have on resource adequacy. We also analyzed the interactions between available transmission and capacity value for VG.**

Keywords-capacity value; power system planning; solar generation; system planning; transmission; wind power generation

I. INTRODUCTION

The increasing electrical load served by variable generation (VG), such as wind and solar energy, in the United States and many other countries has stimulated an interesting line of research to better quantify the capacity value of these resources. Methods applied traditionally to thermal units based on their average outage rates do not apply to VG because of their uncertain and non-dispatchable nature. The North American Electric Reliability Corporation's Integration of Variable Generation Task Force recently released a report that highlighted the need to develop and benchmark metrics that reasonably and fairly calculate the capacity value of solar and wind power [1]. As the fraction of generation coming from VG becomes more relevant, their estimated capacity value will have an impact on system planning [2].

In this paper, we provide a method to include VG in traditional probabilistic-based adequacy methods. This method was implemented in the Renewable Energy Probabilistic Resource Assessment tool (REPRA), which was developed at the National Renewable Energy Laboratory (NREL). Through an example based on the U.S. Western Interconnection (WI), this method was applied to assess a first-order approach of the effect that transmission can have on system adequacy. The results were significant enough to encourage further investigation, which would provide a better estimate of the contribution of transmission and allow a comprehensive analysis of the trade-offs between the addition of new transmission and new generation.

The remainder of the paper is organized as follows: Section II introduces the concept of effective load-carrying capability; Section III describes the REPRA tool used in this study; Section IV provides a numerical example that applies this methodology to the WI; and, finally, Section V concludes and provides future steps.

II. EFFECTIVE LOAD-CARRYING CAPABILITY

Generation system adequacy is the portion of electrical systems reliability that ensures that available capacity is sufficient to meet expected system demand within an acceptable risk threshold [3] at some future date. The metrics most commonly used to assess system adequacy revolve around probabilistic methods based on the loss-of-load probability (LOLP). The loss-of-load expectation (LOLE) is a measurement of the expected days in a year that could face a generation shortfall. Similarly, the loss-of-load hours measures the expected number of hours in a year with insufficient generation.

The literature review in [4] and more recent examples in [1, 5] present the effective load-carrying capability (ELCC) as an emerging suitable metric to evaluate the effect of VG. Given a reliability target, ELCC is defined for a system as the maximum load that could be served by the system while meeting said reliability target. We also can define the ELCC for a generation unit as the increase in the system ELCC when that unit is added to the system. Fig. 1 shows a graphical representation of this definition. The red horizontal line represents the reliability target of 1 day in 10 years, which is a common target used in industry. The blue line represents the reliability curve for the units already in the system, which has an ELCC of 10 GW. When a new generation unit is added, the reliability curve shifts to the right. The horizontal difference between the systems curves, 400 MW, represents the new unit's ELCC.

These calculations can be used to estimate the beneficial contribution to system adequacy from a transmission layout.

Consider the different areas that are connected by said transmission layout. We could calculate the system ELCC for the resources in each area, essentially isolating them from each other. Because it is highly unlikely that the balance of resources and load is evenly distributed along the entire footprint, the transmission system can facilitate the transfer of extra generation capacity to the most problematic areas. Thus, the combination of the individual areas' ELCC will be smaller than that of the entire footprint. The difference between these metrics is the estimated adequacy contribution from the transmission system. The upper bound of this contribution can be found by comparing the individual areas to a copper sheet model, where perfect transmission is assumed between any two points in the system.

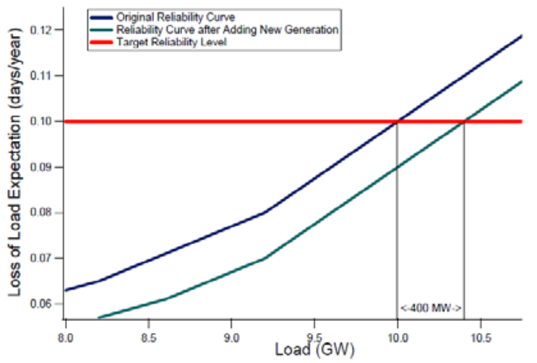

Figure 1. The unit ELCC is the horizontal distance between the reliability curves, measured at the target reliability level (400 MW at 1 d/10 yr).

This methodology was used in NREL's Eastern Wind Integration Study [6], which found that the existing grid transmission system in the Eastern Interconnection provides between 1,200 and 8,500 MW of tie benefits, depending on the load profiles used.

This simple representation of region connectivity allows us to evaluate the potential of performing a more detailed analysis with proper transmission representation. In reality, transmission capacity is a finite and probabilistic value. Transmission lines, like conventional generators, should be represented with a forced outage rate and a maximum capacity. We envision incorporating these capabilities into the REPRA tool, although analytical examples available in the literature are limited to two or three interconnected areas [3,7]. Alternative methodologies include the use of Monte Carlo simulations, e.g., in GE's Multi-Area Reliability Simulations program [8].

III. THE REPRA TOOL

The REPRA tool is being further developed at NREL to better understand how different types of renewable generation, which are usually non-dispatchable 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 most simple case is whether the unit is available or not, with a probability that it is not equal to the Effective Forced Outage Rate (EFOR).

After the convolution of the traditional units [3] 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 instance, 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, one can interpret this cumulative probability as the LOLP associated with a 200-MW load level.

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

Variable generation can be convolved with the capacity outage probability table in a similar fashion. The main difference is the determination of the probability distribution used in the convolution. 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 [9] 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 h. 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 be 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.

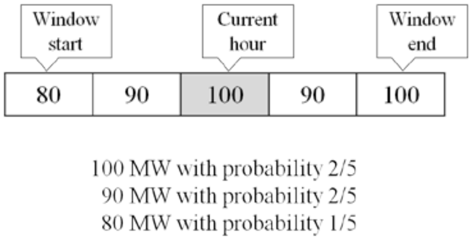

Figure 2. Example of sliding window for wind power generation.

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 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, to 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

A. *Data Description*

In this section, we applied the reliability tool introduced in the previous section to the Western Electricity Coordinating Council (WECC) footprint. The representation of the generation fleet was based on Phase 2 of NREL's Western Wind and Solar Study (WWSIS2) [10]. This data is consistent with other studies performed by the WECC's Transmission Expansion Planning Policy Committee [11].

Table IV contains the list of Balancing Area Authorities (BAAs) that were considered in this example. BAAs were grouped in seven subregions, following the suggested zones in [12], with the only difference being that the Southern California subregion includes the Comisón Federal de Electricidad (CFE). Fig. 3 presents a map of the different BAAs and the subregions they belong to, which are differentiated by different shades. In this example, Western Area Power Association—Upper Great Plains West was merged with Northeast Energy because of the small size of the former.

Load time series data from 2006 was chosen from the Ventyx Velocity Suite [13] 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 [14] developed by 3TIER using a numerical weather prediction (NWP) 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-year 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 NREL [15] based on the satellite-derived irradiance generated by the State University of New York/Clean Power Research [16], which is available on a 10-km grid at an hourly resolution. The resulting data set contains a total of 29 GW of installed wind and 14 GW of solar, which correspond to energy penetrations of 8% and 3% for wind and solar power, respectively.

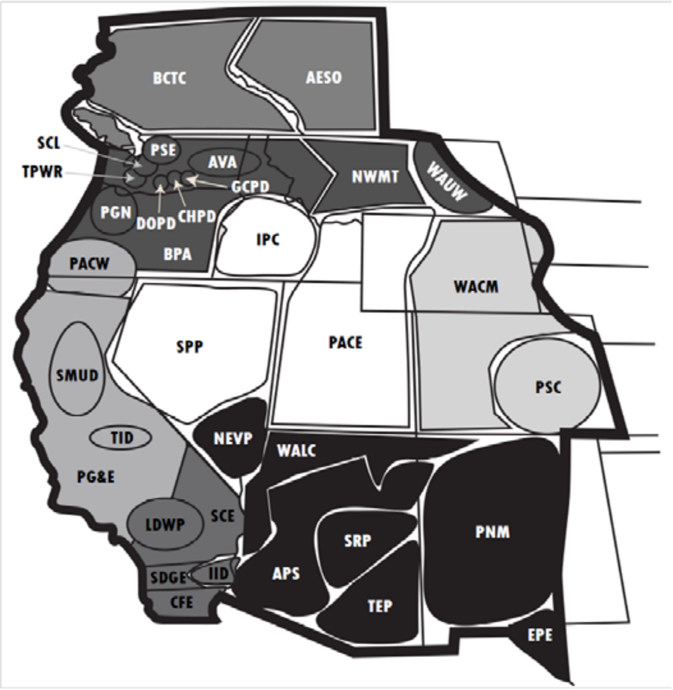

Figure 3. WECC Balancing Authority Areas and subregions.

TABLE IV. BALANCING AUTHORITIES AND SUBREGIONS IN WECC

Subregion	Code	Balancing Authority Area
Canada	AESO	Alberta
	BCTC	British Columbia Transmission Corporation
Northwest	AVA	Avista
	BPA	Bonneville Power Administration
	CHPD	PUD No. 1 of Chelan County
	DODP	PUD No. 1 of Douglas County
	GCPD	PUD No. 1 of Grant County
	NWMT	Northwest Energy
	PGN	Portland General Electric
	PSE	Puget Sound Energy
	SCL	Seattle City Light
	TPWR	Tacoma Power
	WAUW	WAPA—Upper Great Plains West
Basin	IPC	Idaho Power Corp.
	PACE	Pacificorp East
	SPP	Sierra Pacific Power (NV Energy)
Rockies	PSC	Public Service Company of Colorado
	WACM	WAPA—Colorado Missouri Region
Desert Southwest	APS	Arizona Public Service
	EPE	El Paso Electric
	NEVP	Nevada Power
	PNM	Public Service Company of New Mexico
	SRP	Salt River Project
	TEP	Tucson Electric Power
	WALC	WAPA—Lower Colorado Region
Northern California	PACW	Pacificorp West
	PG&E	Pacific Gas and Electric
	SMUD	Sacramento Municipal Utility District
	TID	Turlock Irrigation District
Southern California	IID	Imperial Irrigation District
	LDWP	LA Dpt. of Water and Power
	SCE	Southern California Edison
	SDGE	San Diego Gas and Electric
	CFE	Comisión Federal de Electricidad

B. Results

The methods described in the previous sections were applied to the WI footprint. Table V summarizes the main characteristics of the interconnection and its different subregions. The data included the coincident load peak by region, the number of thermal and hydro units (conventional) and the capacity they represent, and installed wind and solar capacity. The last column included the resulting LOLE when the regions were analyzed by themselves, which was smaller than the usual 1 day in 10 years for the entire interconnection and most subregions. The Basin region and Southern California routinely import energy from other areas, which is consistent with the resulting high LOLE values.

TABLE V. REGIONS CHARACTERISTICS AND BASIC LOLE RESULTS

Region	Peak (GW)	Units	Convent. Capacity (GW)	Wind (GW)	Solar (GW)	LOLE (days/y)
Interconnect	177.6	1901	251.2	29.1	14.3	$< 10^{-10}$
Canada	26.3	298	62.8	4.1	–	$< 10^{-10}$
Northwest	32.2	454	46.5	9.7	1.5	$< 10^{-10}$
Basin	16.4	167	17.0	2.5	–	4.53
Rockies	13.9	164	16.0	3.3	1.1	0.015
Desert SW	33.1	239	40.9	1.3	1.1	$< 10^{-10}$
North CA	28.5	284	31.2	2.4	1.8	0.014
South CA	41.6	295	36.7	5.9	8.8	2.95

ELCC values were calculated with and without a contribution from VG at three levels: interconnection, subregions, and BAAs. In each case, transmission constraints between units in the same area were dismissed. The results for the first two levels are summarized in Table VI, including the maximum peak loads that could be served by the installed generation within each area with an LOLE of 1 day in 10 years. The scale factors corresponded to the ratio between this maximum peak and the actual peak load, shown in Table V. Similar results were found at the BAA level but were omitted here.

TABLE VI. SYSTEM ELCC RESULTS FOR INTERCONNECTION AND SUBREGIONS

Region	VG included		VG excluded	
	Scale Factor	Peak Load (GW)	Scale Factor	Peak Load (GW)
Interconnect	1.373	244.0	1.304	231.6
Canada	2.014	52.9	1.952	51.3
Northwest	1.354	43.6	1.308	42.2
Basin	0.900	14.8	0.883	14.5
Rockies	1.041	14.4	0.979	13.6
Desert SW	1.152	38.1	1.090	36.1
North CA	1.028	29.3	0.985	28.1
South CA	0.884	36.8	0.802	33.3

The smaller regions' VG needed to be properly combined to compare interconnection-wide results for all three aggregation levels. For instance, the load time series for each subregion was scaled using the appropriate factor. The sum of these load series was then used to find the new coincident interconnection-wide peak that could be served without violating the minimum LOLE for each subregion. The same process was performed starting with the BAA data; it is summarized in Table VII. The increase column shows the additional peak load that could be served when higher levels of aggregation were compared to the isolated BAA case. According to these results, perfect transmission between BAAs in the WI would allow the system to supply an additional 60.3 GW of peak load when VG is factored in. Half of that extra load could be served if we considered only perfect transmission within each subregion.

TABLE VII. COINCIDENT PEAK LOAD AND AVERAGE POWER BY AGGREGATION LEVEL

Region	VG	Peak Load (GW)	Increase (GW)
Intercon.	Yes	244.0	60.3 (33%)
Subregion		209.4	25.7 (14%)
BAAs		183.7	
Intercon.	No	231.6	56.3 (32%)
Subregion		199.3	24.0 (14%)
BAAs		175.3	

The relative increase in peak load that could be served was very similar whether or not VG was factored in: 33% for perfect interconnection transmission and 14% for infinite intra-subregional transmission. Additionally, we examined the contribution of VG to the system adequacy by calculating the differences between the same aggregation levels with and without renewables. The results are displayed in Table VIII and correspond to the ELCC for the combined wind and solar power present in the system and their average capacity value. Fig. 4 represents the relative capacity value for wind and solar, along with combined VG. All values increased with the level of aggregation, which suggests that transmission also has a boosting effect on the contribution of VG to system adequacy.

TABLE VIII. ELCC AND CAPACITY FACTOR FOR RENEWABLES BY AGGREGATION LEVEL

Region	VG ELCC (GW)	VG Capacity Value (%)
Intercon.	12.4	28.2
Subregion	10.1	23.0
BAAs	8.4	19.1

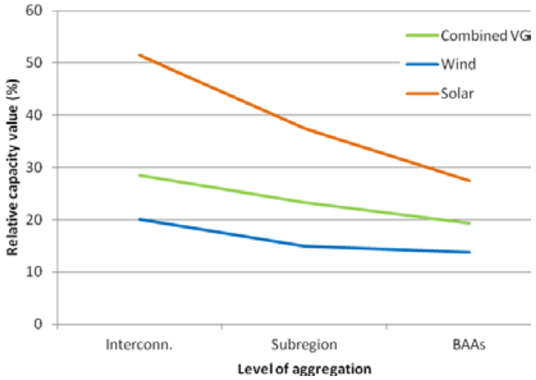

Figure 4. Capacity value for wind, solar, and combined VG.

Finally, we examined the capacity value for wind and solar at the interconnection level and also for each of the regions considered. There was a large spread in the capacity values for all categories. In general, PV capacity values were larger than wind, except for Northern California, where wind capacity values were slightly larger. PV capacity values in the Desert Southwest were extraordinarily large, even with almost 2 GW installed in the region. Interconnection values constituted a reasonable average of the different regions.

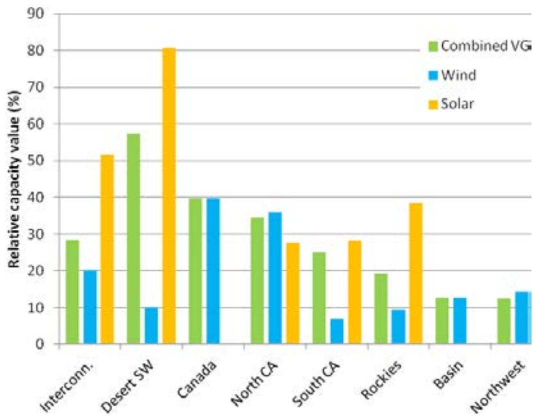

Figure 5. Capacity value for the interconnection and regions.

V. CONCLUSIONS

The methodology presented here is promising in quantifying the beneficial contribution of transmission to electric system adequacy. To gain a better understanding of this contribution, this approach needs to be applied to other cases, including alternative footprints, historical time series data, and penetration levels of renewable generation.

The numerical example in this paper analyzed the contribution that perfect transmission has in the adequacy of a system. The results indicate that this contribution is significant. Furthermore, additional transmission enhances the capacity value of variable generation.

The promising results suggest that further work should be done to extend the methodology so that it is possible to enforce actual transmission constraints and force outage rates, as opposed to the copper-sheet analysis used in this paper. The result of this work will produce a more accurate estimation of the value of transmission in terms of resource adequacy.

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