# Capacity Value of Wind Power

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Capacity Value of Wind Power

Task Force on the Capacity Value of Wind Power, IEEE Power and Energy Society

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Abstract—Power systems are planned such that they have adequate generation capacity to meet the load, according to a defined reliability target. The increase in the penetration of wind generation in recent years has led to a number of challenges for the planning and operation of power systems. A key metric for system adequacy is the capacity value of generation. The capacity value of a generator is the contribution that a given generator makes to overall system adequacy. The variable and stochastic nature of wind sets it apart from conventional energy sources. As a result, the modeling of wind generation in the same manner as conventional generation for capacity value calculations is inappropriate. In this paper a preferred method for calculation of the capacity value of wind is described and a discussion of the pertinent issues surrounding it is given. Approximate methods for the calculation are also described with their limitations highlighted. The outcome of recent wind capacity value analyses in Europe and North America are highlighted with a description of open research questions also given.

Index Terms—Wind power, capacity value, effective load carrying capability, power system operation and planning

I. INTRODUCTION

POWER system reliability is divided into two basic aspects, system security and system adequacy. A system is secure if it can withstand a loss (or potentially multiple losses) of key power supply components such as generators or transmission links. System adequacy refers to the issue of whether there is sufficient installed capacity to meet the electric load [1]. This adequacy is achieved with a combination of different generators that may have significantly different characteristics. Capacity value is the contribution that a given generator makes to overall system adequacy. It can be defined as the amount of additional load that can be served due to the addition of the generator, while maintaining the existing levels of reliability.

The metrics that are used for adequacy evaluation include the loss of load expectation (LOLE) and the loss of load probability (LOLP). LOLP is the probability that the load will exceed the available generation at a given time. This criterion only gives an indication of generation capacity shortfall and lacks information on the importance and duration of the outage. LOLE is the expected number of hours or days, during which the load will not be met over a defined time period. The contribution that any given generator makes to overall system adequacy, as measured by LOLE, or similar reliability metric is called the effective load carrying capability (ELCC). ELCC is the standard metric by which the capacity value is judged. A generator’s ELCC is the additional load which the system can support on addition of the new generation, while maintaining the same LOLE level [2].

The topic of capacity value of wind power has been attracting attention in recent times with a number of publications dealing with this issue [3-7]. Currently a wide range of approaches have been implemented in academia and industry, each with their own inherent limitations and approximations. This paper is the result of work undertaken by the Taskforce on Capacity Value of Wind, which was proposed by the Wind Power Coordination Committee and Power Systems Analysis, Computing and Economics committee of the IEEE Power and Energy Society (PES). The overall objective of the taskforce has been to provide clarity on the calculation of capacity value of wind. This paper is the outcome of the taskforce meeting and panel session which took place at the IEEE PES General Meeting in Pittsburgh, 2008.

The paper classifies the current approaches used for the assessment of the capacity value of wind power generation. In particular, a preferred method is recommended and described in detail in Section II. Other approximate methods are described in Section III, with the limitations of each highlighted and recommendations made as to their usage. The results of relevant international studies are described in Section IV. A description of open research questions in this area are given in Section V, with conclusions and recommendations given in Section VI.

II. PREFERRED METHODOLOGY

A. Method Description

This method is based directly on the definition of capacity value given above. Conventional thermal generation is still the most common form of generation in power systems. They are modeled by their respective capacities and forced outage rates (FOR). Each generator capacity and FOR is convolved via an iterative method to produce the analytical reliability model (capacity outage probability table (COPT)) of the power system. The COPT is a table of capacity levels and their associated probabilities [1]. The cumulative probabilities give the LOLP for each possible available generation state. Wind power cannot be adequately modeled by its capacity and FOR as wind availability is more a matter of resource availability than mechanical availability. This leads to a different treatment...
of wind generation in the traditional ELCC calculation method, which is now summarized in the following three steps:

1. The COPT of the power system is used in conjunction with the hourly load time series to compute the hourly LOLPs without the presence of the wind plant at least one year. The annual LOLE is then calculated. The LOLE should meet the predetermined reliability target for that period. If it does not match, the loads can be adjusted, if desired, so that the target reliability level is achieved.

2. The time series for the wind plant power output is treated as negative load and is combined with the load time series, resulting in a load time series net of wind power [8]. In the same manner as step 1, the LOLE is calculated. It will now be lower (and therefore better) than the target LOLE in the first step.

3. The load data is then increased by a constant ΔL across all hours using an iterative process, and the LOLE recalculated at each step until the target LOLE is reached. The increase in peak load (sum of ΔLs) that achieves the reliability target is the ELCC or capacity value of the wind plant.

B. Factors Influencing Capacity Value Calculation

For thermal units, the primary characteristics that influence the overall system adequacy are the units’ available capacity and FORs. Long-term FORs are typically available by type and size of unit, compiled from a large data set of similar units. Modelling wind power using 2-state distributions in this manner is not recommended as wind is a highly variable resource which cannot be adequately modeled by a two state model.

With respect to wind power, the relationship between the wind and the load is a key factor to be captured by the calculation method. The correlation between wind and load is site dependent. In some areas there is a diurnal and/or seasonal wind pattern. Although the hourly correlation between wind and load can be nearly zero, there may be a considerable correlation among wind and load data when binned according to rank. A physical mechanism for this may be that load extremes are often due to relatively infrequent large-scale high-pressure weather systems that typically bring calm winds. This implies the existence of systematic patterns of wind generation during system peaks and other time periods that cannot be ignored. As an example, data used in the Minnesota 20% Wind Integration Study [9] was used to calculate correlation coefficients by deciles (10 equal divisions) and vigiciles (20 equal divisions). The results are shown in Fig. 1. The figure shows the relative ranking of wind and loads by dividing them into deciles and vigiciles (10 and 20 equally-sized bins) and is based on the average wind or load within the grouping. The annual correlation coefficient of the hourly wind and load data is relatively small at -0.158. However, after computing the midpoints of each decile and basing the calculation on those, the correlation coefficient is considerable at -0.908, and the corresponding vigicile correlation coefficient is -0.889. Therefore, it is critical to use hourly wind and load data from the same year so that the underlying relationship between wind and load is implicitly captured in the modeling. The linear correlation coefficients provide limited information about the relationship between two variables, but are used here as part of a simplified illustration.

Fig. 1. Correlation between wind and load based on deciles and vigiciles

Although the key driver of wind capacity value comes from the general correlation of wind and load, it is important to remember that ELCC is a function of many different system parameters. Some of these include hydro generation schedules (generally highly correlated with load), import-export schedules (often high imports are correlated with load), and maintenance schedules for conventional units. This latter impact can occur if maintenance outages have a significant impact on LOLP during shoulder seasons, and if there is significant wind generation during those times [9]. The geographic dispersion of both wind and load will also impact ELCC, as will the wind penetration level.

Fig. 2 illustrates the effect of an additional generator on the reliability curve, where it is seen to move to the right. ELCC is the contribution to overall adequacy, represented by the movement of this curve. The case illustrated uses the common LOLE target of 1 day/10 years. This target, although commonly used, can be changed to reflect the acceptable risk level of the region. The selected target reliability level can have a large impact on the capacity value of both conventional power and wind power [4]. When the target reliability level, is lower, and LOLP higher, there is relatively more value in any added capacity than in cases where LOLP is very low [10]. It should be noted that 1 day/10 years daily LOLE should be interpreted as “at sometime during 1 day in 10 years”. Therefore, a 1 day in 10 years LOLE target will be more reliable and is distinct from a 24 hours in 10 year target. A common approach is to estimate LOLE and related indices for one balancing area of the whole interconnection, e.g. for a utility, a state or a country. The interpretation of LOLE is then not “Loss of Load Expectation”, but instead expectation of requirement to import. In many systems where the calculations show a given expectation of capacity deficit, the true
a non-zero probability of available imports which are not otherwise accounted for in the analysis. The impact of imports could be modeled within the preferred method if the data is available for the interconnections into the system. For comparison of capacity values between systems, the system is initially modified to give a standard LOLE value such as 1 day in 10 years, this then allows comparison of the capacity value of wind between systems. This does not give a true measure of the adequacy of the systems where LOLE values are different, but allows for wind’s contribution to be assessed and compared against other systems that used this standard value, as well as compared against other energy sources.

The input data employed is a key factor in the calculation of capacity value. It should be noted that regardless of the method employed, if sufficient data of the required quality is not available, the resulting answer cannot be relied upon. The preferred method requires:

1) Load time series for the period of investigation (multi-year is preferable)
2) Wind power time series for the same period as the loads
3) A complete inventory of conventional generation units’ capacity, forced outage rates and maintenance schedules

The length of the period of investigation required is an open question with wind power. For wind and other variable generators, it has been common practice to use one or more years of hourly generation data to calculate wind’s ELCC. This approach, although a reasonable start, does not adequately represent the long-term performance characteristics of wind power plants in the same way that long-term representations are made for conventional units. Multiple years of data are preferred as there can be a significant inter-annual variation of the wind resource [11]. The exact number required is dependent on a number of factors including the size of the system, load curve and penetration of wind power on the system. The overall output for each year is important, but the timing of the wind output is also a very important factor to be captured. This reemphasizes the need for time synchronized data with the load.

Wind data of the required quality and quantity has been scarce to date due to many wind plants only being recently installed. In addition, this time series data can be commercially sensitive, making it harder to obtain. For other energy resources such as hydro power, this is less of a problem as it is a well established, mature technology with decades of good quality data often being available. As noted above, calculation of the “true” multi-area LOLE and related indices should consider possibilities of import. This means that representative time series for import levels and their respective likelihoods in neighboring systems should be used.

### III. APPROXIMATE METHODOLOGIES

This section outlines some of the approximate methodologies that have been employed for calculation of capacity value. They are included as a means of contrast with the preferred method and also to highlight the approximations and assumptions they make.

It is important to note that with modern computing power the preferred method is not overly time-consuming for moderately sized systems; indeed, a multi-year calculation can be run in a matter of seconds on a desktop PC. Approximation methods must therefore be justified on grounds of ease of coding, or on grounds of greater transparency which aids the interpretation of results.

#### A. Garver approximation based methods

Garver proposed a simplified, approximate graphical approach to calculating the ELCC of an additional generator [2]. This has been an important method in the calculation of capacity values but has been superseded by advances in computing power. Although the paper’s focus was on the graphical approach, the same underlying methodology can be used to estimate the ELCC of a wind generator added to a given power system. Garver’s approximation and its extension to multi-state units [6] are based on two main assumptions:

- The multi-state unit representation of wind described below is used; the probability distribution for wind availability is the same at all times.
- The LOLE before addition of the wind may be approximated as $B e^{md}$, where $d_0$ is the peak demand, and $m$ and $B$ are fitting parameters.

The ELCC ($\overline{d}$) of the wind generation is then calculated as

$$\overline{d} = -\frac{1}{m} \ln \left( \sum_i p_i e^{-mw_i} \right) \quad (1)$$

where $p_i$ is the probability that the available wind capacity is $w_i$.

#### B. Multi-state unit representation

An alternative risk calculation to the preferred method is the multi-state approach, which utilises a probabilistic representation of the wind plant [8], [6]. Similarly to conventional units with de-rated states, the wind plant is modeled with partial capacity outage states each of which has an associated probability. To evaluate the LOLP at a given time, the wind generation is included in a COPT calculation in the same manner as a multi-state conventional unit. The
ELCC calculation then proceeds as described in the preferred method, except using the modified calculation.

The multi-state model for wind power is typically constructed from a histogram of the wind power output for the chosen period. A major concern associated with this approach is the loss of information on wind/load correlation. In most regions there is significant seasonal and diurnal variation in wind energy availability, as well as effects of weather on demand; these cannot be adequately described by a single probability density function for all periods. This concern may be addressed to some extent by using different probability distributions for different categories of hours. The total LOLE would then be evaluated by adding the LOLEs from the various categories of hour. However, such a modification still does not fully account for any correlation between demand and wind availability. Such effects will be captured automatically when the preferred methodology is employed.

C. Annual peak calculations

Loss of load probability at time of annual peak demand is used as a proxy for system risk in some regions, for example Great Britain has generally followed this practice [12], [13]. The definition of ELCC for peak calculations remains the same as for year-round risk calculations, except that the risk index used is LOLP at time of annual peak. It follows that probability distributions are required for the demand and available wind capacity at time of annual peak (the distribution for available conventional capacity is derived via a COPT calculation, as in the preferred ELCC calculation method.)

The requirement for a probability distribution for available wind capacity is problematic, because peak demand by definition occurs once a year, and hence by definition the available data is very limited. Two approaches which have been used in investigating the wind resource at annual peak are:

1) Use a histogram of hourly load factors for the entire peaking season. This has the disadvantage that many days are not close to annual peak demand, so their relevance is limited if the wind/demand correlation is substantial.

2) Use a histogram of load factors from hours where demand is within a certain percentage of that year’s peak. This ensures greater relevance to peak demand, at the expense of reducing the amount of data used.

The main criticisms of an annual peak calculation are that it does not explicitly consider loss of load at other times of the year, and that it is difficult to obtain appropriate probability distributions for the wind resource at annual peak, and also for the peak load.

D. Peak-period capacity factors

There has been considerable interest in using capacity factors (average output) calculated over suitable peak periods to estimate the capacity value of wind. Some of these approximations are reasonably accurate [4]. In [14] a good approximation was achieved only if hydro and import-export transactions were ignored. As discussed previously, this is no surprise because hydro and transaction schedules are often positively correlated with load. Although capacity factor approximations may be useful as quick screening methods (for instance, a higher capacity factor would usually imply a higher capacity value on the same system), we do not endorse them here as they do not capture the short term or annual variability of wind power, or the correlation of wind availability with demand.

E. Z Statistic Method

The z-statistic method [7] is based on taking the difference between available resources and load over peak demand hours (surplus availability) as a random variable with an associated probability distribution. The z-statistic for that distribution (mean divided by standard deviation) is taken as the primary system adequacy metric. The incremental load carrying capability for an added power plant is taken to be the load addition that keeps the z-statistic constant. For small changes in the overall system, keeping the z-statistic constant is equivalent to maintaining a constant LOLP. This approach is therefore an approximate method for annual peak ELCC calculation. The following assumptions are involved in its formulation:

- the shape of the probability distribution for the margin of available capacity over demand does not change significantly on adding the wind (though the mean and standard deviation (SD) may change).
- the SD (σ) of the distribution for wind availability is small compared to the SD (σ) of the distribution for available capacity from the existing generation.

These allow a transparent closed-form expression for ELCC to be derived. The method is most conveniently stated by regarding the z-statistic for margin as a proxy for LOLP. The ELCC (\( \bar{d} \)) is then the load addition that keeps the z-statistic constant:

\[
\bar{d} = \mu - \frac{z_0 \sigma^2}{2 \sigma}
\]  

(2)

where \( \mu \) is the mean wind load factor over peak load hours, and \( z_0 \) is the z-statistic representing the LOLP level. Due to it being a perturbation method, and due to the assumption that the shape of the distribution for available margin is unchanged, it is especially accurate for small incremental wind penetrations, and progressively less accurate for evaluating large increments of wind generation on a power system.

This method’s principal advantage lies in the transparency of the formula for ELCC; it provides greater insight into what influences the level of ELCC than iterative calculations. The usefulness of the method is in providing a relatively simple rapid method for determining how wind variability and correlations among wind projects affect the load carrying capability.

IV. CASE STUDIES

This section presents summary results from capacity value studies around the world. In each of the studies different
methods have been applied which partly explains why there are differing capacity value levels. There are also differences between the results of the studies due to the differing characteristics of the wind and demand profiles in each of the regions under study.

A. New York State Study

The objective of this study was to assess the effective load carrying capability of future wind resources in the State of New York [15]. The preferred method in Section II was used with the addition of considering the power transfer limits of the tie lines between different control areas. The historical NYISO hourly load data for 2001, 2002 and 2003 at different buses were used. The wind power plants were assumed to have 3,300 MW installed capacity, of which 600 MW were assumed to be off-shore. Available historical meteorological data for the same years were used to create time series for hourly wind power generation at different sites. The time synchronized data for loads and output wind power were used in the analysis to maintain their correlation. The LOLP analysis was performed while considering the transfer limits on the tie-lines between the pairs of interconnected areas. The hourly loads for 2001 and 2002 have been modified to be in per unit based on the 2008 peak load.

Results show that most of the reduction in LOLP comes from the 600 MW offshore site. The sites to the west of a major system transmission interface have minimal effect on LOLP due to congestion in the transmission. For 2001, the ELCC for the 3,300 MW of wind generation is 270 MW, i.e., 8% of nameplate capacity, if the transmission constraints are removed the ELCC increase to 720 MW (22% of nameplate capacity). Overall, the onshore in ELCC is about 10%. Some of the LOLE analysis results are shown in Fig. 3.

B. Minnesota State Study

The study was performed in 2006 [8]. Different levels of wind generation 3,441 MW, 4,582 MW and 5,688 MW which correspond to 15%, 20% and 25% as a percentage of the forecasted Minnesota retail electric sales in the year of 2020 were assumed. Conventional generation was expanded to meet the criteria of LOLE of 1 day/10 years for the year of 2020.

Wind generation was represented as negative load as per the preferred method. The analysis was conducted for three different versions of year 2020, where the hourly wind and load patterns are based on the historical years 2003, 2004, and 2005. The LOLE analysis was performed using a commercial reliability evaluation software package to construct the COPT for the non wind and the three wind penetration scenarios. The exact method described in Section II was used to evaluate capacity value for each penetration scenario. The study results are summarized in Fig. 4. It can be seen that the effective capacity of wind generation can vary significantly year-to-year. The ELCC of the wind generation corresponding to 15% 20% and 25% wind penetration ranges from approximately 5% to just over 20% of nameplate capacity.

Meteorological conditions are the most likely explanation for the trend in the ELCC by year. The highest ELCC values were obtained in 2003 as this year shows the best correlation between wind production during the highest load hours while the lowest ELCC values were obtained in 2005 as this year exhibits the poorest correlation.

C. German Wind Integration Study

The DENA grid study is a German wind integration study which was carried out from 2003 to 2005 [16]. One section covers wind’s contribution to the secured capacity at the time of winter peak. The secured capacity stands for the amount of capacity that power plants can deliver at a defined security level. This is a different concept to the capacity value as defined here in this paper and consequently, this method does not address system adequacy and is not based on ELCC since load data is not explicitly considered. It is included here as it is widely quoted as a capacity value analysis.

The probability functions of wind power generation are based on measurements of up to 220 stations covering up to 10 years of data. Different probability functions resulting from different time frames (coldest days, winter peaks, winter months) and different spatial distribution scenarios (more / less offshore wind farms) are analyzed. The assumed security level is 99% so the generation capacity that is available with a certainty of 99% is compared before and after the addition of wind generation. Conventional generating units with a FOR that exceeds 1% would not achieve this security level.

As has been shown in [4], [5], overall system adequacy of any desired level can be achieved with individual units that have higher outage rates; for example multiple units with 0.85 forced outage rates can achieve a reliability target of 1 day in
10 years.

**D. Irish Wind Study**

The Irish wind study from 2004 examines the impact of Irish wind power generation on the conventional power plants [17]. The calculated capacity value of wind generation is equal to the amount of conventional capacity that can be omitted whilst maintaining the same LOLE. This definition of capacity value is distinct from that recommended here, where capacity value is defined in terms of additional load. The definition in terms of additional conventional capacity requires the definition of a notional typical conventional unit to measure the ELCC against. The hourly wind power generation is modeled as negative demand and added to the hourly load profile capturing corresponding correlation effects. This corresponds to the preferred methodology in Section II. Measurements of 18 onshore wind stations and 1 offshore station for the year of 2001 served to model the wind power profile. The reference LOLE is 8 h in one year.

Capacity values of wind generation in a 5 GW peak system and a 6.5 GW peak system consisting of more and more modern conventional power plants are calculated. In the former system the capacity value of 0.5 GW installed wind capacities is 34% of installed capacity. Assuming 1.5 GW it decreases to 23% of installed capacity. The same amount of capacities show a slightly lower capacity value of 22% in the second system dropping to 14% with 3.5 GW of installed wind capacities.

**E. Comparisons Between Studies**

A report on the state of the art of wind integration by the IEA Wind Task 25 compiled the results of these and other wind integration studies into a single document and provides useful comparisons between methods and countries/regions [18]. It is apparent from the results described above that the capacity value is dependent on the method employed but it also depends on the specific characteristics of the region/country. In particular, the characteristics of the wind regime and the characteristics of the demand profile, e.g. whether peak demand occurs in winter or summer. Fig. 5 shows summary results from some of the studies described above and some others described in [18-20]. It shows the decrease of relative capacity value with increasing capacities of wind. It also shows that this decrease is a common feature across all the systems studied. The lower values in Germany are partly due to the lower average wind power production compared with Ireland, Norway, UK and US, and partly due to the different methodologies used. Fig. 5 is reproduced from the IEA Wind Task 25 State of the Art report [19].

**V. OPEN RESEARCH QUESTIONS**

There remain a number of open research questions surrounding the calculation of capacity values. These range from the representation of other generation types in the calculation method to the data requirements for calculations. To calculate the ELCC of a conventional generator one uses the long-term forced outage rate in the COPT and therefore obtains a long-term capacity value for that unit. In any given year, the unit in question could experience a forced outage during the peak period (however defined) and would therefore not deliver on its long-term capacity value. For that specific year the unit’s capacity value would not be representative of the true long term capacity value. The use of long-term synchronized load and wind data is encouraged, keeping in mind the difficulty in using old load profile curves to represent the future. However, capacity value calculations are normally based on data sets over limited time periods, but the statistics of the available data sets may not be representative. This becomes more critical if several stochastic variables are present. The relationship patterns between wind and peak load for example vary strongly over different years. It would be valuable to have some estimation of the possible deviations of capacity values that are related to different time periods and hence quantify the impact that limited data sets can have on the calculation results.

Currently, the inclusion of maintenance schedules in the preferred calculation can have an influence on the calculated LOLE. Maintenance schedules in reality may have some flexibility, and if faced with a severe capacity deficit, scheduled maintenance can in some instances be deferred. This may call into question the use of deterministic maintenance schedules in capacity value calculations and would be worth investigating.

The applications of capacity value are in planning. However, the unique characteristics of wind power are giving rise to new interactions between the planning and operations timeframes. Calculations based on a weekly or daily timeframe, with very precise knowledge of system conditions, are necessarily different to those performed under the greater uncertainty of a planning timescale, thus leading to a new concept related but distinct from capacity value. Specific factors that may have influence in this regard are maintenance schedules, unit ramping and certain transmission constraints.

This paper has covered the treatment of wind resources only. As they move towards commercial development, the capacity value of other variable resources such as wave, solar and tidal should also be considered. This will require
VI. CONCLUSIONS AND RECOMMENDATIONS

This paper has described a preferred method for calculation of capacity value of wind generation. Key metrics employed in the calculation have been defined. The employment of time synchronized load and wind power output data that captures their correlation is vital. Representation of wind as a two state probability model or assessment of wind’s capacity value at peak times is inadequate. Factors such as the correlation between different wind sites and with the load, the geographical area and the target reliability level have been shown to have a considerable impact on the capacity value.

A number of the common approximate methods for capacity value of wind have been described. The accuracy of these methods is varied and while some may be useful given limited data, it is important to be clear about the approximations being made. It has been shown here that there is a best practice method for the calculation of capacity value of wind power, but that any calculation is subject to the sufficiency of the available data. A brief description of current open research question has also been given. Several international studies in this area have been undertaken. A summary of the results of these studies has been given, illustrating that diverse methods and wind resources lead to a wide range of values for the capacity value of wind power.

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