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Reconsidering the capacity credit of wind power: Application of cumulative prospect theory

Edgar Wilton [a,*], Erik Delarue [b], William D'haeseleer [b], Wilfried van Sark [a]

[a] Copernicus Institute of Sustainable Development and Innovation, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[b] University of Leuven (KU Leuven) Energy Institute, TME Branch (Applied Mechanics and Energy Conversion), Celestijnenlaan 300A, Box 2421/B-3001 Leuven, Belgium

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ABSTRACT

The capacity credit is often erroneously considered to be a time-invariant quantity. A multi-year analysis of the incident wind profile of various potential wind sites uncovered that there exist large differences between annual capacity credit figures. The uniformity of these capacity credit figures is found to decrease with diminishing wind time series interval lengths. In recognition of the resulting uncertainty, decision maker risk propensity toward various capacity credit scenarios was investigated by adopting cumulative prospect theory. The methodology proposed in this paper is an extension of the effective load carrying capability method. It enables the quantitative analysis of the attitudes of decision makers with regard to deviations (gains and losses) from the forecasted capacity credit as a result of the uncertainty of the incident wind profile. Here, gains and losses may not be viewed by decision makers as having equal but opposite effects on the appeal of wind power production. Therefore, it is argued that a decision maker will not have a neutral risk propensity toward changes to the outcome of the capacity credit and will discount increases and decreases of the loss of load expectation according to a non-linear preference. In line with the well-known adagium that losses loom larger than gains the value of the capacity credit is found to be lower than its corresponding least squares forecast.

1. Introduction

Since the adoption of the '20-20-20'goals [1], several EU countries have acknowledged that increasing their use of wind power could significantly aid in lowering their greenhouse gas emissions. However, any successful attempt to transition to a power system with high installed wind capacity levels will need to take into consideration that on occasion there will be periods of little to no wind due to the intermittent nature of this resource. Therefore, in order for a power system to perform its intended function, reliably supplying electricity to the end-consumer, the magnitude of the contribution of wind power generation to the reliability of the power system needs to be determined.

Next to the need for load-balancing during average-load days, a stable power system must also possess enough installed reserve capacity to deal with unexpected contingencies. The latter is referred to as a power system's adequacy. Adequacy determines the degree to which a power system has sufficient generation facilities to satisfy consumer demand. This is not to be confused with the security of a power system, which evaluates how well a system is able to handle local or widespread disturbances, such as the loss of one (or several) generating units [2].

A well-documented method for assessing the adequacy of a wind power generation system is by determining its capacity credit (CC) (e.g. Ref. [3]). This can be defined as *the amount of additional load a system can serve as a result of the addition of a generator without altering the existing reliability level* [4].[1]

The investigation of the value of wind power and the effects of the time series length on the CC performed in this paper was prompted by a growing awareness that sudden extended low wind periods may have severe consequences for the system reliability of power systems with a high wind power penetration. For instance, it is stated in Leahy and Foley [6] that it is likely that the CC is sensitive to the occurrence and frequency of extreme weather events. Furthermore, in Gilotte [7] it is recognized that the CC does not take

* Corresponding author.
E-mail address: edgar.wilton@gmail.com (E. Wilton).

[1] It should be noted that the CC can also be defined as the amount of *conventional power generation capacity reduction* that can be achieved without affecting the loss of load probability (e.g. Ref. [5]).

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into consideration that the increased power outage probability, resulting from extended periods with low wind availability, may not be compensated by a reduction of the power outage probability during periods with relatively abundant wind availability.[2] In other words, the typical decision maker may value equal magnitudes relative to a reference point differently depending on whether they are categorized as 'gains' or 'losses' relative to some expectation level. Consequently, it can be argued that the CC should be valued according to a methodology that incorporates this reference dependence. Therefore, in this paper the use of cumulative prospect theory (CPT) is proposed for the first time as an extension of CC analysis.

CPT is a fully empirical descriptive decision theory that derives the value of an uncertain prospect by means of a frame, a value function and a non-linear decision weighting function. It is rooted in behavioral psychology and has demonstrated to possess sufficient explanatory power for use in actual decision making problems [8]. It is argued in this paper that it could also be used to address the issue of properly valuing the occurrence of deviant weather patterns. This is especially true when the time series interval (TSI) on which the CC is evaluated is reduced to a length of several weeks. The reduction of the time series interval reveals the underlying variability of the incident wind profile. Furthermore, this segregation of the wind time series enables the identification of extended low wind periods that would otherwise have gone unnoticed as a result of the inconsequentiality of a bi-/triweekly time frame on the typical measurement interval of one year.

This paper begins with a brief literature review of the utilized capacity credit methodology, an investigation of the use of CPT in engineering literature thus far and a description of its foremost characteristics. Subsequently, the proposed methodology is applied to a case study where a high installed wind capacity is added to the existing thermal generation capacity of the Netherlands. Afterward, the results are presented, discussed and the main findings are summarized in the conclusion.

2. Literature review

2.1. Capacity credit

The International Energy Agency (IEA) considers computation of the effective load carrying capability (ELCC) of a power system, by means of a loss of load probability (LOLP) analysis using chronological load demand patterns, to be the most rigorous methodology available for estimating the CC [9]. This claim is backed by the Institute of Electrical and Electronics Engineers (IEEE), which also appears to favor the ELCC method for assessing the CC [4].

The ELCC method analyzes the capacity credit from an incremental load addition standpoint. Here, it is assumed that thermal generators are still relatively abundant and that the overall system reliability can be modeled by means of their rated power output and forced outage rate (FOR) alone.

Over sufficiently large time intervals, the FOR can also be approximated by dividing the forced outage hours by the sum of the in-service hours and forced outage hours [2]. The FOR and rated capacity values of the thermal generator set are subsequently used to determine the capacity outage probability table (COPT). The cumulative probability values corresponding to each of the various possible available generation states can then be used to determine the LOLP, which is given by

$$\mathrm{LOLP}_t = P\left(\sum_{g=1}^{G} C_{g,t} < L_t\right) \tag{1}$$

where $C_{g,t}$ represents the rated capacity of generator g, during hour t and L_t equals the load demand during hour t. As discussed by Kahn [10], when determining the LOLP values over a certain time frame, the LOLP can be used to derive the expected power outage length over that time frame. The acquired variable is the loss of load expectation (LOLE), which can be defined for any particular time interval, given that it is measurable on the unit scale of the LOLP (in this case hours t), as follows

$$\mathrm{LOLE} = \sum_{t=1}^{T} \mathrm{LOLP}_t \tag{2}$$

Here, T denotes the TSI length. Furthermore, it should be noted that a common planning objective is the '1-day-in-10-years' reliability criterion, which implies a system reliability of approximately 99.97% [10].

Garver [11] defined the ELCC as the magnitude of the incremental lo ad addition ΔL that can be supported by a system at the initial LOLE following a certain capacity addition ΔC. An implicit definition of the ELCC can then be given by stating that the initial LOLE, with a given incremental load addition, may not exceed a predetermined power system reliability criterion (LOLE_R). The corresponding value of the ELCC can subsequently be ascertained by iteratively determining the maximum incremental load addition ΔL:

$$\max_{\Delta L \in \mathbb{R}^+} \Delta L \qquad \text{(Objective function)}$$

$$\sum_{t=1}^{T} P\left(\sum_{g=1}^{G} C_{g,t} + \Delta C < L_t + \Delta L\right) \le \mathrm{LOLE}_R \qquad \text{(Reliability constraint)}$$

This approach, although ideal for classical thermal generation stations, does not allow for the adequate analysis of systems with intermittent power sources, such as wind turbines. This is due to the fact that for wind turbines the capacity and FOR are more dependent on the availability of wind resources than on mechanical constraints. Therefore, in order to accurately incorporate wind generation, the time series of the wind power plant output is treated as *negative* load demand considering that all the load that is served by wind power does not have to be supplied by thermal generators. The difference between the ELCC with and without the addition of wind power is considered as the CC of a certain installed wind capacity.

2.2. Cumulative prospect theory

It has been noted that the study of wind power consists of two relevant time horizons [12]. These are the short-term, which includes the decisions pertaining to the optimal wind energy offerings and conjoining levels of operational backup, and the long-term, which foresee the capacity backup investments that will be necessary to ensure the continued adequacy of the power system. Risk assessment is already extensively featured in short-term modeling practices. That is, several methodologies have been developed that either mitigate some form of risk associated with the profits realized from wind power generation [13,14] or allow the attitudes of dispatchers with regard to risk and cost to be included in dispatch and unit-commitment models [15,16].

With regards to the long-term, it has been argued in Gilotte [7] that the LOLE, being an expectation, is risk-neutral by nature. Considering that decision makers have been known to be

[2] Moreover, the massive overcapacity during extended periods of wind abundance places additional stress on the system, potentially *increasing* the LOLP.