# A New Reliability Criterion for Calculating Wind System Capacity

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***Abstract*— After correcting for wind system capacity (WSC), the load imposed on the wind system's dispatchable generators should never be greater than the corresponding no-wind system peak requirement. This criterion contrasts with a common method of maintaining reliability on average, some years less, some years more. Reliability should be maintained at all times, not on average. The primary factor determining WSC is wind-load correlation, the occasional combination of high load and low wind. New "fat tail" empirical evidence is presented. 67 years and 12 regions are analyzed. Most regions have some years with low annual contribution of wind to system capacity (awsc), flat with penetration. To preserve reliability, the minimum awsc is an upper bound on WSC. Thus, for a given region, WSC ≤ min[awsc(year)]. For the regions studied, average regional WSC is found to be small, <2.5% of wind nameplate, ranging between <0.1% and <7.5%.**

***Index Terms*—Wind capacity, reliability, system planning**

## I. Nomenclature

Dispatchable generators: Generators controllable on demand with forced failures independent of each other.

Nameplate: Manufacturer rated max continuous power.

Residual load: Load to be reliably serviced by dispatchable generators. The residual load profile is calculated by concurrently subtracting hourly wind from hourly load.

EDF - Exceedance Distribution Function: The probability that the system power is greater than a given power level.

ELCC – Effective Load Carrying Capability: a statistical methodology for calculating the power that systems of independent generators can reliably deliver to a load.

LOLE – Loss of Load Expectation: a reliability requirement taken to be 1 dy/10 years; 1dy/3654dy or a 0.00027 probability that load exceeds generation capacity.

LOLP – Loss of Load Probability: the probability that generation fails to meet load requirements at a specific time.

awsc – For a given year, the difference between the annual load peak and the annual residual load peak.

WSC - Wind System Capacity: the amount of additional load that can be served due to the <u>total wind</u> in the system, while maintaining no-wind levels of peak reliability.

## II. Introduction

This research extends work presented in two papers, the first is by the *IEEE Task Force on the Capacity Value of Wind Power* [1]. That paper proposed a preferred methodology whereby wind is modeled as negative load. The negative load methodology correctly preserves historical wind-load correlations. Modeling wind deterministically (negative load) results in a residual load distribution that must be reliably satisfied by dispatchable generators. Keane [1] combines independent dispatchable generators with wind generators exhibiting correlation in space, time and load to compute an ELCC. This method has been extended to the Irish grid in [2].

The second paper is *MISO's Planning Year 2014-2015 Wind Capacity Credit* [3], taken as illustrative of current industry practice in systems with significant amounts of wind. MISO Staff averages residual peaks to determine WSC without consideration to variance.

### A. To maintain system reliability

To preserve engineering practice, the requirement that a wind system "maintain the reliability" of a no-wind system should mean that wind system reliability is never less than that of a no-wind system.

Specifically, system planners typically establish a peak system load requirement to size the no-wind system dispatchable reserves. Adding wind increases the load that can be carried by an amount equal to WSC. After correcting for WSC, reliability is maintained if the residual load imposed on same set of dispatchable generators is never greater than the no-wind peak system load requirement.

From another perspective, adding wind increases the volatility of the load that must be satisfied by dispatchable generation. That increased variance should not be ignored by assuming that reliability is maintained "on average". Higher reliability at low loads does not offset lower reliability at high loads. All of the increased volatility must be reliably offset. That is: WSC ≤ min[awsc(year)], not WSC = avg[awsc(year)].

### B. Organization of this paper

A high level system concept model is proposed to focus on structural relationships. Two important aspects of wind statistics are spatial correlations, leading to total wind modeled as a single generator, and wind-load correlations leading to the wind as negative load perspective. METHODOLOGY reviews ELCC analysis using exceedance functions. The negative load perspective shows how awsc is calculated. ANALYSIS compares this paper with [3] concluding that the calculations are the same; the difference is min. vs avg. awsc. A side by side comparison shows that average awsc leads to large LOLP at the residual peak. The method is then applied to 12 diverse regions within North America and Europe including both summer and winter peaking systems. Most regions contained at least one year in which wind output was low during high system load and flat with wind penetration. A second important discovery is that the residual load exhibits "fat tails" at high load. That is, the occasional combination of high load and low wind is not a rare outlier but the repeatable result of normal weather.

## III. BACKGROUND

### A. A system concept model introduces clarity

The chosen system concept model consists of wind turbines and dispatchable fossil fuel generators; no storage, or other generator types. Boundaries are closed with no imports, or exports. The system is required to satisfy historical load profiles and historical wind generation profiles. Wind production is scaled to four levels, 10, 20, 30, 40% of load. Curtailed wind, small at these penetration levels, is deleted.

This closed system model is consistent with the first stage of traditional engineering development. That is, start with models that include essential features (real wind & load profiles), then add complexity in stages [4]. The purpose of this concept model is to understand relationships (between reliability, wind, load and dispatchable generation) priority and focus. System dependent benefits of cooperating with neighboring regions and other generator types can be evaluated at later stages and is beyond the scope of this paper.

### B. A high level perspective

Fig. 1 presents the production time series from about 3,000 wind turbines in the PJM system during 2013. PJM is in the U.S. Northeast and coordinates wholesale electricity across 13 states. The red bars on the horizontal axis denote those hours when wind production is less than 1% of nameplate; a total of 94 hours. Low production occurs in August, a peak load season. This correspondence suggests that WC is likely to be small.

Fig. 1 is typical of other years and regions. Wind on the Irish grid was <1% for 154 hours in 2013.

Fig. 2 contrasts EDF for dispatchable thermal generators and standalone wind. Both systems have the same nameplate, 100 power units.

The solid red curve corresponds to 100 equal size independent generators each with a random forced outage rate of 3%, (typical of well-maintained natural gas turbines during peak demand [4]). The strong shoulder on this curve means that this system can deliver high power at high reliability and makes efficient use of capital hardware. It is possible that all 100 could fail simultaneously, but the probability of such an occurrence is infinitesimally small $(0.03)^{100} \approx 10^{-153}$. At lower power levels, exceedance asymptotically approaches unity. Dispatchable generators can fail abruptly, but, such failures are independent of each other so the loss of one generator is

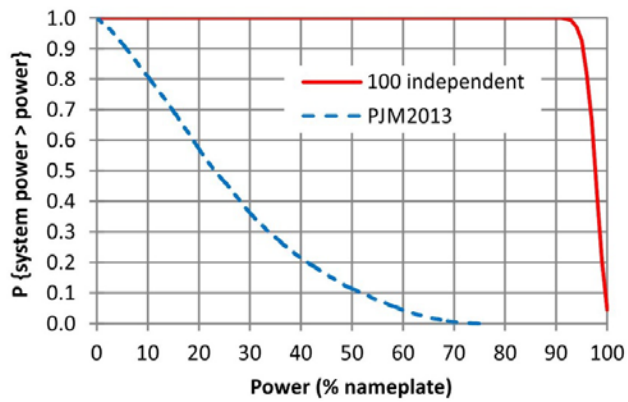


Figure 2 - EDF for wind and fossil fuel systems

perhaps 1% of total generation on a large grid, a ripple.

The blue-dashed curve is the exceedance of standalone wind on PJM for 2013, the same data set illustrated in Fig. 1. In contrast to the high reliability of independent generators standalone wind system can go to zero for ~100 hours/year.

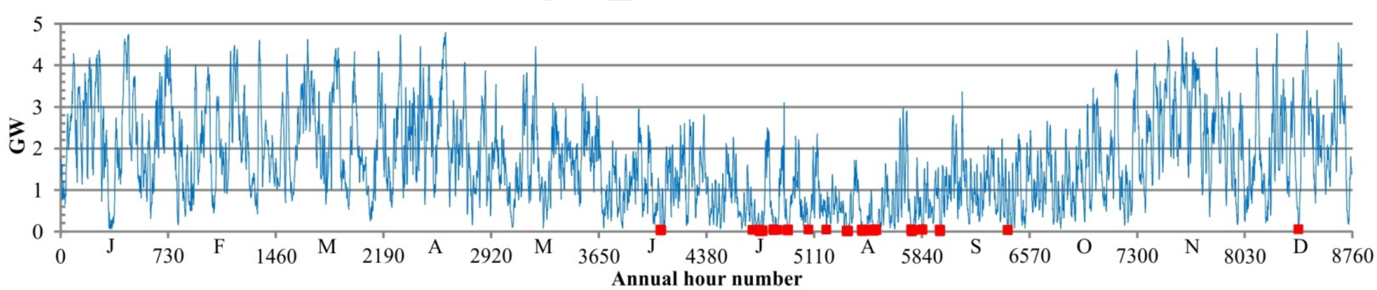


Figure 1 - PJM2013 wind production

### C. Wind Statistics Are Different

Wind power statistics are very different from those for fossil fuel systems. While the forced failures of fossil fuel generators are random and independent of each other, wind turbine production exhibits unknown correlations with space, time, load and other wind turbines. It is also continuously variable rather than discrete, not controllable (dispatchable), and exhibits significant seasonal (Fig. 1) and annual variation [2], [3]. These temporal variations mean that wind generation and system statistics are non-stationary.

### D. Wind is modeled as a single generator

The common definition of wind system capacity is: "*the amount of additional load that can be served due to the addition of a generator, while maintaining the existing levels of reliability*".[1] The definition in NOMENCLATURE differs from this in that the word "generator" has been replaced by "total wind." Capacity is a property of a system, not specific generators. Capacity contribution can be allocated to specific generators only if the generators are independent of each other. Unlike dispatchable generators, wind turbines exhibit unknown correlations with each other and with load that cannot be ignored.

Spatial correlations can be correctly accommodated by measuring total wind production on the system as a single unit (this is common practice). A subset of wind turbines does not make a unique contribution to WSC; the contribution changes, depending on what other turbines are on the system.

### *E. Wind-load Correlations*

There is evidence of occasional combinations of high load and low wind. Keane et al [1] reports: "*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*." Keane then cites a Minnesota study showing negative wind-load correlation of -0.9 at highest 5% of load [1].

Fig. 3 presents similar results for the UK National Grid. Available data is 5 minute readings of wind electric power production for 36 months June 2011 through Mar 2014. The dashed curve shows the form of the wind electric power density suitably normalized so that the average annual power is 10 units (horizontal axis). For each of the three 12 month periods, wind histograms are developed for 120 intervals (10 hours) corresponding to the highest load. The solid red bar histograms for the winter of '12-'13 show that for the 10 hours of highest load, almost all of the wind production was below average. Wind is negatively correlated with peak load for that year. For the other two years there appears to be no significant correlation between wind production and peak load.

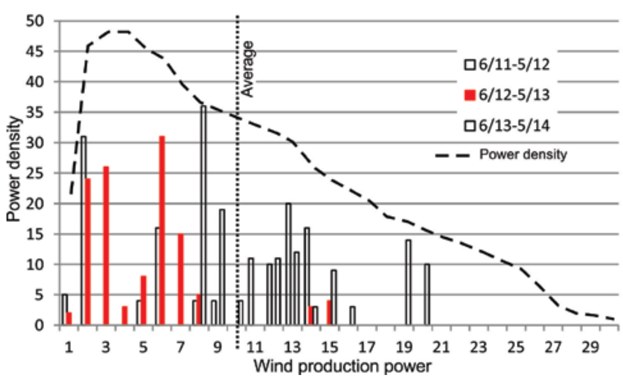


Figure 3 – National Grid power density & histograms

This occasionally strong wind-peak-load correlation is a "tail event," obscured in overall averages and many scatter plots. Since capacity calculations are driven by load peaks it is essential that this correlation be preserved in the analysis.

### *F. The flaw of averages*

Popular literature describes the dangers of averaging non-Gaussian statistics [5]. The cartoon example is a lake that averages 3 ft. depth with one sinkhole that is 15 ft. deep. That sinkhole is a "fat tail" that needs deterministic analysis.

A similar situation occurs when a small electric power system has a single large generator, say a nuclear plant sized at 10% of average load. The nuclear plant needs to be viewed deterministically i.e. sufficient spinning reserves to satisfy load if the plant trips, and sufficient reserves to maintain reliability when it is taken off line for extended periods of maintenance.

Given the observed wind-peak-load correlations and the fact that total wind can be a significant fraction of average load, the hypothesis is that the wind system has fat tailed statistics. The occasional combination of high load and low wind is the primary design criterion that determines WSC.

## IV. Methodology

The method compares a system of independent dispatchable generators with the same set of dispatchable generators plus wind. Within the constraints of the system concept model, the capacity of both systems is determined by annual peaks. For the no-wind system it is the system peak load. For the wind system it is residual peak; the peak of the residual load-minus-wind profile that must be satisfied by dispatchable generators.

### *A. Effective Load Carrying Capability (ELCC)*

ELCC analysis was originally developed by Garver [6]. This section explains the method using more intuitive exceedance curves rather than Garver's COPT tables.

Since all generators have a finite mechanical failure rate, the calculation of a load that the system of generators could carry, ELCC, becomes a statistical problem. Planners may specify a reliability criterion such as a Loss of Load Expectation (LOLE). Fig. 4 shows how to calculate the ELCC from a required LOLE using the EDF. Exceedance can be calculated from the number of generators, their respective size and forced outage rate, using either a Monte Carlo simulation or the binomial theorem.

The Fig. 4 exceedance curve is calculated for 100 one unit size conventional generators, each with a forced outage rate of 3%. The system has a nameplate capacity of 100 units and an average capacity of 97 units. The insert shows how ELCC can be calculated from a LOLE requirement. A one-in-ten LOLE (0.00027) means that system exceedance requirement is 0.99973. System ELCC is defined by where this exceedance requirement crosses the exceedance curve; 90.2 power units for this example. This corresponds to a 9.8% reserve.

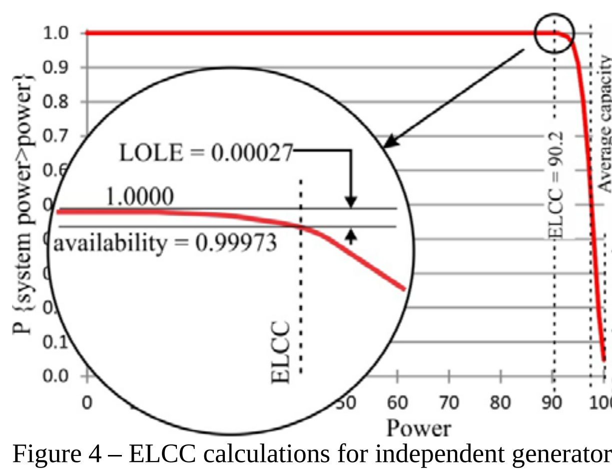


Figure 4 – ELCC calculations for independent generators

It has been noted that while LOLE estimates the probabilitry of loss of load, it does not account for the depth of the shortfall [7, p. 15], viz. the shape of the tail of the distribution. ELCC methodology proviodes a sound basis for comparing similar systems (e.g. a large number of similar sized independent generators). Applying ELCC directly to wind generators does not provide a sound basis for comparing wind with dispatchable generators because the EDFs are different.

*B. Wind as Negative Load*

Keane [1] adapted classical ELCC methodology to systems consisting of wind plus dispatchable generation. Their key creative insight was to view wind as negative load and calculate ELCC for the dispatchable portion of the system. This method preserves wind-load correlation and applies the one-in-ten heuristic to dispatchable generators.

Given a load time series and wind production time series, a third time series is constructed by subtracting hourly wind from concurrent (same hour) load. The resulting residual load profile (load-minus-wind time series) is the load that must be reliably serviced by dispatchable generators.

Fig 5a illustrates the PJM2012 load and load-minus-wind CDFs. For PJM2012, average wind was 1.6% of average load. Anticipating the ANALYSIS section, this wind profile was scaled to 10% of annual load by multiplying each hour wind by 6.25 before subtracting it from concurrent load. Scaling assumes no change in the geographic wind deployment footprint. Fig. 5a shows CDFs for load (solid black) and load-minus-10%wind (blue dashed) calculated from the time series.

Fig. 5b expands the upper right hand box of Fig. 5a. Wind

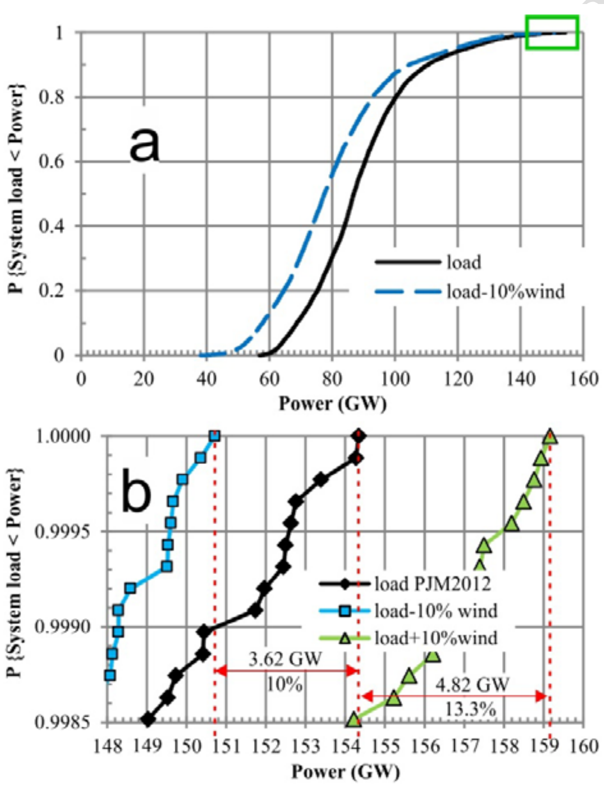


Figure 5 - PJM2012 load CDFs +/- 10%wind

contribution to system capacity is the difference between peak load (black diamonds) and peak load-minus-10%wind (blue squares); 3.62GW. Therefore awsc is 10% of scaled wind nameplate (36.1GW) for that specific region, year and wind penetration.

When viewing wind as negative load, the appropriate basis for comparing load is peak-hour, a CDF = 1; not (1-LOLE) which applies to generation exceedance, not load. System planners forecast load using a variety of methods, the most sophisticated of which is weather normalization [8]. Within the constraints of the system concept model the peak load requirement is assumed to be a deterministic number.

*C. Note: Subtract, do not add wind to concurrent load*

The ANALYSIS section compares the results of this paper with those of the MISO Staff. When calculating wind contribution to ELCC it is important to subtract wind from concurrent load, not add wind to concurrent load as the MISO Staff appears to do. Subtracting wind from concurrent load (blue squares) results in a physically meaningful load CDF corresponding to the strategy of dialing back on dispatchable generators whenever the wind is blowing. For PJM2012, peak stress on dispatchable generation no longer occurs at peak load (hr. 4769) but 11 days earlier (hr. 4505). Adding 10% wind to concurrent load results in an unphysical (nonsense) load CDF (Fig. 5 green triangles). That system concept model assumes that consumers are going to increase consumption just because the wind is blowing.

*D. WSC is determined by residual peak load*

The blue dotted curve in Fig. 6 is MISO's daily system peak hour load. For no-wind systems, dispatchable generators need to reliably manage system peak hour loads. The solid black lines are daily residual peak hour loads for 40% average wind penetration. The residual load profile was calculated as described in §III-B. For wind systems, dispatchable generation needs to reliably manage residual peak loads.

From Fig. 6 it is clear that wind reduced the daily system peaks, particularly during the spring and fall. There are gaps between the residual peaks and the minimum (weekend) system peaks. There are a couple of days when the residual peak is zero, meaning that wind is curtailed for the whole day. It is also clear that wind does not do much to reduce the extreme system peaks.

A case in point is the Fig. 6 insert for 2009. The system peak load for that year was 100.6 GW. Wind scaled to 40% of annual load reduced that peak to 99.3 GW. Therefore wind contribution to system capacity (aswc) was 1.3 GW for that year. Dividing by nameplate scaled to 40% wind (83.9GW) results in awsc(2009) =1.6% at 40% wind penetration.

This method of focusing on the delta, the difference between the annual system peak and the annual residual peak, effectively normalizes the system peaks. With four years of data we get four awsc samples. Since awsc is the difference between peaks, there is no assurance that another year of data might not result in a smaller difference. Therefore a consequence of the limited data set is that the upper bound for WSC is the minimum awsc of historical record and is preceded by a "<" sign.

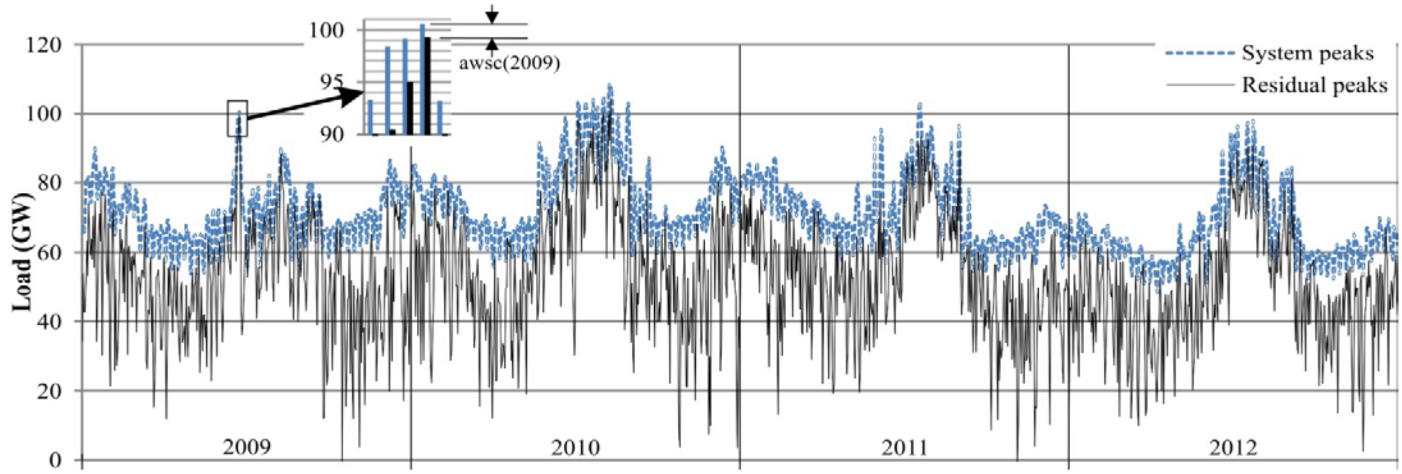


Figure 6 - MISO daily peak loads, 40% wind

## V. ANALYSIS

This ANALYSIS begins with MISO [3] because MISO publishes the hourly time series data, is nearly transparent in their analysis, and historical awsc calculations concur with this research. The central difference is how to transition from historical awsc data to a future WSC requirement.

### A. MISO calculation of awsc

MISO publishes concurrent hourly wind and load time series data for the years 2008-2014 [8]. Fig. 7 shows this paper's awsc estimates (solid lines) as a function of wind penetration defined as average wind as a % of load.

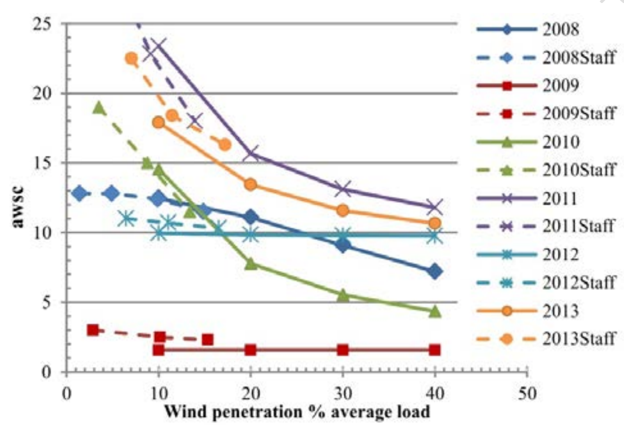


Figure 7 - MISO wsc results

The MISO Staff also calculated awsc using the same data set [3]. The MISO Staff results are also presented in Fig. 7 as dashed lines with each year having the same color and marker as the authors' calculation. The legend for the MISO calculation is suffixed with "Staff." Note that the MISO calculation uses a different penetration definition (nameplate as % of peak load) so the abscissa for the MISO calculation is scaled accordingly to match our definition (average wind as % of average load). The difference between the two sets of results is small and explained by the fact that the MISO calculation was scaled from a chart and that MISO appears to add, not subtract, concurrent wind from load. For a given year, the awsc curve slopes down to the right because the residual peak-hour keeps changing as more wind is added to the system. For 2009, residual peak-hour does not change. The curve is flat at 1.6% corresponding to high load and low wind. The residual peak-hour did not correspond to lowest wind.

### B. Side by side min(awsc) vs. avg(awsc), MISO at 10% wind

The second column of Table 1 shows MISO peak load in GW for each year. For each year, hourly wind was scaled to 10% of average load. Then wind was subtracted from concurrent load to create a residual time series. The residual peak (GW) for each year is presented in column 3. Each year is normalized to have the same peak load, arbitrairly chosed to be 90.20 power units. The corresponding normalized residual peak (that must be reliably serviced by dispatchable generation) is presented in column 5.

Table 1 MISO, wind @ 10% of load

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Year | System Peak load | Residual Peak | Normalized system peak | Normalized residual pk |
| 2013 | 95.40 | 92.22 | 90.20 | 87.19 |
| 2012 | 98.03 | 96.16 | 90.20 | 88.48 |
| 2011 | 103.50 | 98.50 | 90.20 | 85.84 |
| 2010 | 108.35 | 104.92 | 90.20 | 87.34 |
| 2009 | 100.58 | 100.25 | 90.20 | 89.90 |
| 2008 | 97.06 | 94.51 | 90.20 | 87.83 |
| average | | | | 87.77 |

The solid red curves in Fig. 8 all have the same dispatchable generation EDF illustrated in Fig. 4. With an LOLE reliability requirement of 0.00027, the system of 100 independent generators has an ELCC of 90.2. Such a no-wind system can reliably service a peak load as high as 90.2.

Fig. 8a adds 10% wind to that same system of 100 independent generators. With system peaks normalized to 90.2, wind reduces the annual load peaks that must be serviced by dispatchable generation down to the normalized residual peaks presented in Table 1, col 5. These residual peaks are presented as black triangles along the power axis in Fig 8a. Each of the black triangles corresponds to an LOLP that is less than 0.00027. For a load of 90.2, the wind system is more reliable than the no-wind system for each year of historical record.

Table 1 shows that the limiting year, the year with the

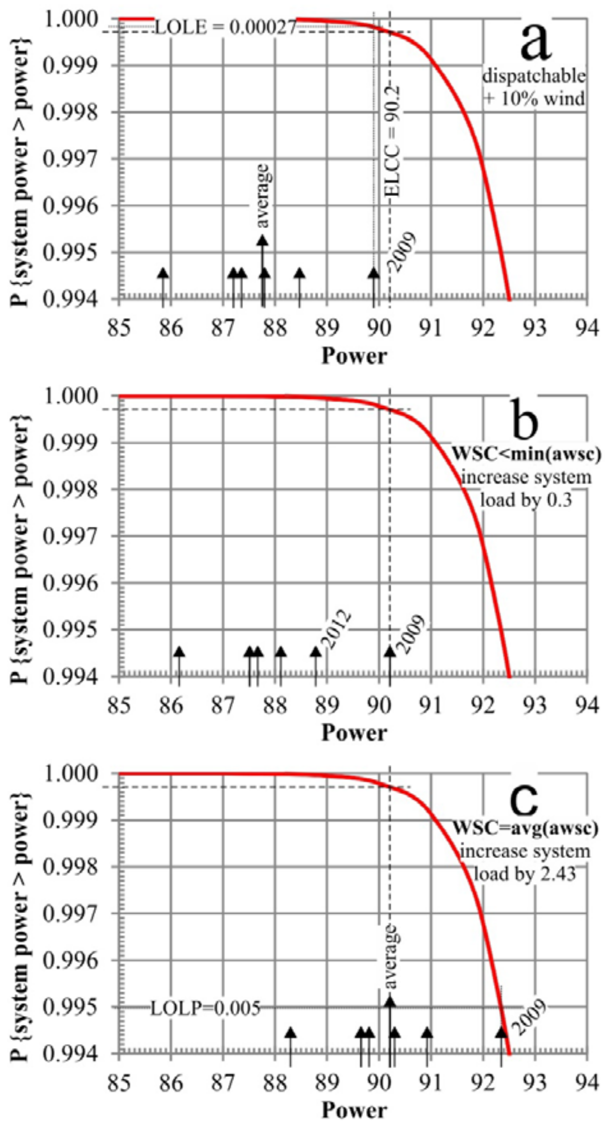


Figure 8 - MISO systems with 10% wind

largest residual peak, is 2009. The criterion that WSC<min(awsc) means that the addition of wind allows the system load to be increased by <0.3 power units, raising the residual peak from 89.9 to 90.2 units, the reliable ELCC of the no-wind system. Increasing the residual peaks by <0.3 units results in the system configuration of Fig. 8b. The 10% wind system can support load an additional load of <0.3 power units with a reliability that is equal to or greater than the no-wind system. That is, each and every year of historiocal record has a LOLP equal to or less than 0.00027.

Averaging column 5 in Table 1 results in a forceast residual load of 87.77 power units down 2.43 power units from the normalized system peaks of 90.2 units (Fig. 8a). The criterion that WSC=avg(awsc) is illustrated in Fig. 8c. This averaging criterion results in a system that is not as reliable as the no-wind system because there are three years when LOLP is substantially greater than the no-wind LOLE. Indeed, as a result of the non-linear decline in the dispatchable EDF, the 2009 LOLP has increased from 0.00027 to 0.005 (Fig. 8c).

The central argument of this paper is that all of the wind induced variance must be reliably managed. Only if all of the residual peaks have an LOLP less than or equal tro the no-wind LOLE is reliablility maintained. The practice of averaging results in a system that has the same reliability as the original no-wind system on-average, some years less some years more. Capacity is driven by system peaks. The authors reject the notion that somehow the smaller LOLP for below average years offsets the substantially larger LOLP for above average years.

### C. Multiple Region WSC Analysis

Table 2 summarizes the results for multiple regions and years for which suitable data was found. Required data is concurrent wind and load time series at intervals of one hour or less, as well as installed wind nameplate capacity. Details of the calculations, data sources, regional graphs of wind contribution to system ELCC and unique characteristics of certain regions are presented in an addendum [9].

Table 2 - Multiple region analyses

| Region | Years | WSC |
|---|---|---|
| Midwest Integrated system operator* [8] | 2008-2013 | <1.6% |
| PJM Interconnection, LLC | 2012-2013 | <3.4% |
| Irish grid* | 2004-2014 | <0.6% |
| Alberta Electric Systems Operator* | 2009-2012 | <0.1% |
| Ontario Electric Systems Operator | 2006-2013 | <2.7% |
| UK National Grid | 6/11-5/14 | <3.4% |
| Electric Reliability Council of Texas | 2007-2013 | <2.7% |
| Denmark* | 2006-2013 | <2.0% |
| France | 2011-2013 | <7.5% |
| Germany | 2011-2013 | <2.0% |
| NordPool | 2012-2013 | <3.8% |
| Bonneville Power Administration* | 2007-2014 | <0.2% |
| Total years / average WSC | 64 | <2.5% |

### D. WSC is independent of penetration

Fig 9 shows EirGrid awsc results. For many years, the awsc curves sloped down to the right as the residual peak load hour changed with increasing wind penetration. However, there are

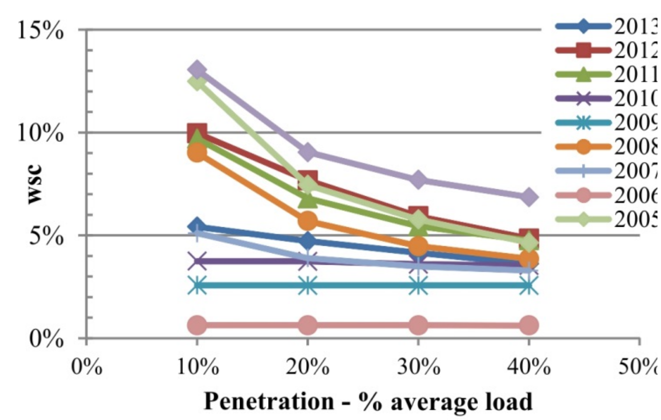


Figure 9 - EirGrid (Irish Grid) wsc results

three years where awsc is flat and low. The flat curve for EirGrid 2006, 2009, 2010, suggest that WSC is independent of penetration and the marginal contribution of wind to system capacity does not change with wind penetration

### *E. Fat tail evidence*

Fig. 10 is a scatterplot of residual load as a function of system load. Since residual load is system load minus wind, zero wind corresponds to the 45$^o$ line. For a given system load wind increases downward from zero to nameplate (~40GW). So the lower boundary to the scatter plot is also a 45$^o$ line displaced downward 40 GW below the zero wind 45$^o$ line.

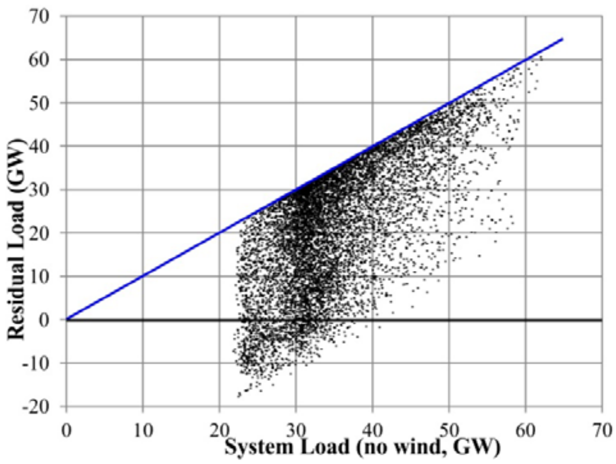


Figure 10 - ERCOT 2007 @ 40% wind shows fat tail

The left hand boundary is formed by minimum system load, about 23 GW. The right hand boundary is interesting. The 8760 data points do not uniformly populate a parallelogram as they would if wind were independent of load. As system load increases, wind begins to hug the zero wind line, high load corresponding to low wind. This is definite evidence of a fat tail forming at high loads, at least for 2007.

## VI. DISCUSSION

WSC is determined by residual peaks, the fat tail, the negative correlation between wind and high load. The wind as negative load perspective correctly accounts for this negative correlation. This perspective makes the WSC analysis deterministic, not statistical. The original contribution of this paper is to require that the system with wind be at least as reliable as the corresponding no-wind system at all times. WSC is the amount of load that can be added such that the residual peaks for the wind system never exceed the system peaks of the no-wind system with the same set of dispatchable generators.

### *A. Results*

- For certain years, the residual load profile exhibits fat tails at system high load.
- With limited data, there is no assurance that additional years will not exhibit greater residual peaks. Therefore the best that can be determined is an upper bound to WSC.
- For the regions investigated, WSC is a percentage of nameplate in the low single digits with some variation from region to region (Table 2).
- Some awsc curves decline with penetration (Fig. 9): This is a result of changing residual peak hours. The awsc curve is flat and low when the residual peak hour does not change. Many regions (those with most data) experience occasional years with awsc flat with penetration. Occasionally flat and low is likely to be a general result.
- Is has been observed that residual peaks do not necessarily occur during the same hour as peak system load or minimum wind.
- Within the constraints of the system concept model, off-peak capacity has no value.

### *B. Future work*

- The impact of small WSC on system costs and the markets for capacity and energy needs definition.
- The method should be applied to solar PV system concept models and to different wind/PV combinations.
- The method can quantify the result of combining regions. Smith [10] contemplated a hypothetical connection of PJM & MISO for 2012. WSC was improved, but only by 0.3%.
- Strengthen results (§V-A) with more analysis of specific systems.
- France WSC estimate is anomalously high. It is unclear whether this is corrupted data or something significant.
- Gradually introduce real world complexities, different generator types, storage, and import/export.
- The limits and boundaries of ELCC methodology to compare systems with different statistics (e.g. Large nuclear plant on a small system) are poorly understood. Where is the practical boundary between statistics and determinism?
- Adequately meeting peak capacity is only one measure of system reliability. The change in operating characteristics due to intermittent renewable generation must also be better understood as it relates to having sufficient generating resources and reserves available.

## VII. WSC CONCLUSIONS

There is agreement that WSC should be chosen so that the wind system "maintains the reliability" of the no-wind system. Yet MISO Staff estimates WSC=14% while this paper concludes MISO WSC $\leq$ 1.6%. The difference is that the common approach maintains reliability on average; WSC = avg(awsc). This paper argues that reliability must be maintained at all times; WSC $\leq$ min(awsc).

Introducing wind increases the volatility of the load that must be satisfied by dispatchable generators. The authors argue that all of that increased variance needs to be reliably supported. The authors reject the averaging argument: that lower LOLP at lower residual peaks (when there are lots of idle dispatchable generators) somehow offsets higher LOLP at higher residual peaks (when all assets are needed).

Garver's original conception of ELCC employed a deterministic peak load requirement and independent generators. Efforts to generalize ELCC assume that a residual load distribution can be computed. The authors argue that the many important correlations prevent this and the problem needs to be analyzed deterministically. WSC is determined by peak loads, residual peaks, the occasional combination of high load and low wind. These residual peaks are not outliers, but fat tails, part of repeatable wind patterns.

A small WSC is not unexpected as there needs to be a physical basis for capacity. Dispatchable system capacity is based on the parallel connection of generators with independent forced outages. The probability of losing all power from only 5 generators, each with a 3% independent forced outage rate, is a remarkable $10^{-8}$. In contrast, there is no empirical evidence that standalone wind systems have capacity. If wind was positively correlated with load then there would be a physical basis for significant WSC, but the empirical evidence is that the correlation is negative, not positive. There needs to be a physical reason why plugging wind into a grid significantly increases capacity.

While WSC=0 is a conservative approximation, it is reasonable that WSC is >0. Since total wind is independent of other dispatchable generators, total wind may have an impact similar to any other independent generator. With a system of 100 independent generators this impact would be ~1%.

Applying this method to 67 years of data over 12 regions results in an average regional WSC of <2.5% of wind nameplate with a range between regions of <0.1% and <7.5%. This is considerably smaller than published capacity estimates. Dispatchable generation is still required to reliably satisfy most of the system peak load requirements.

This paper supports the perspective that wind is primarily an energy resource, not a capacity source.

## VIII. Acknowledgements

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## X. Biographies

Alex Pavlak (M'1995),. b 1945, received his Ph.D in mechanical engineering from Stevens Institute of Technology and holds a PE license. He has 45 years' experience developing various first-of-a-kind systems. He started his career with the Apollo project, and then worked on ballistic missile development. In the 1970's he co-founded and became the president of ConSuntrator Inc., a solar collector development company based on patented Solyndra-like optics. In the 1980's he led a team that invented and developed a revolutionary sonar system concept for detecting quiet submarines for the US Navy. In the 1990's he lectured on Modern Tiger Teams and is currently Chairman of the Future of Energy Initiative.

Cynthia Bothwell (M'1994), received her B.S. degree in Electrical Engineering from the University of Illinois, an MBA from Edgewood College, an M.S. degree in Statistics from the University of New Mexico and an M.S. degree in Industrial Engineering from New Mexico State University and holds a PE license. She has over 25 year of experience in the electric utility industry in various engineering planning roles, most recently with Public Service of New Mexico as the Director of Integrated Resource Planning. Currently she is a student of Johns Hopkins University. Her interests include electric system planning and operations including renewable and demand-side resources, system reliability and energy policy.