SERI/TP-35-375

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INTEGRATION OF INTERMITTENT SOURCES INTO BALERIAUX - BOOTH PRODUCTION COST MODELS

SEPTEMBER 1979

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TO BE PRESENTED AT THE
INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC. WINTER POWER MEETING,
DECEMBER 1979, NEW YORK, NEW YORK

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A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

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Abstract - An intermittent generation source is one over which a utility dispatcher has minimal control with regard to the amount of power available at any instant. The power may fluctuate freely over the range from zero to some maximum. Examples of such sources are wind machines, photovoltaic cells and, in some cases, run-of-river hydro. For a utility planner this form of resource presents problems in the determination of reliability and worth. A method of integrating these resources into a utility production cost model is presented; the method should improve approximations in production costing and in the loss-of-load calculation.

INTRODUCTION

In electric utility planning measures of the risk of failure to meet load are extremely important. These measures are used in determining the value of a new source to a system mix and in expansion planning for the system. Historically, the introduction of the Calabrese loss of load calculation (LOLP) was an improvement over the "per cent reserve margin" and hence became a popular reliability measure. With the introduction of production codes based on Baleriaux-Booth theory, the probability of failure to meet load could be obtained directly from an equivalent load duration curve. By multiplying this probability by the hours for which the load duration curve is applicable, one obtains the loss of load hours as the measure of risk. Since an expanded form of the LOLP calculation is equivalent to the Baleriaux-Booth measure, the latter measure has the advantage of giving production cost values and the corresponding loss of load probability from the same computer run.

However, when one examines sources other than those which are conventional fossil or nuclear fueled, one can run into problems with the Baleriaux-Booth codes. In particular, if one is analyzing a source which supplies energy intermittently or in variable amounts within an hour period, then one does not get a true probability of failure to meet load if the input data is based on hourly values. In particular this problem arises with wind or solar sources, and to a lesser extent with a highly variable run-of-river source.

This paper will: (1) demonstrate the equivalency of LOLP methods and the Baleriaux-Booth method for conventional sources, (2) show that the failure of the equivalency to hold in the case of intermittent sources is due to a correlation between load and energy availability and the use of hourly input data, (3) suggest alternative methods for calculating reliability measures for intermittent sources. (These alternate methods would enable one to calculate the economic measure which is commonly called a capacity credit.)

Equivalency Between Measures

The historical Calabrese LOLP calculation used 260 hours for the failure to meet load calculation. The 260 hours consist of the peak hour per day for the five weekdays in fifty-two weeks (1 x 5 x 52). If one expands the calculation hours to every hour of the study interval and if one weights the LOLP value for the hour with the probability of the hour, the equivalency of the Baleriaux-Booth measure can be demonstrated.

For what follows, the following assumptions will be used:

1) loss of load is defined as the failure to meet load due to the failure of generation resources

2) the outage of a source will be patterned after a conventional source, namely that at a given instant we conceive of the plant as being in one of a very limited number of availability states. This is in contrast to the intermittent resource which is often regarded as possessing great variability in output, ranging over zero output to full output in a small time interval.

FORMULATION

The equation for the Baleriaux-Booth measure of reliability is

$$\Pr\left\{\left[\tilde{L} - \sum_{i=1}^{N} \left(CAP_i - \tilde{FO}_i\right)\right] > 0\right\}$$

where

$\Pr$ = probability

$\tilde{L}$ = load regarded as a random variable

CAP_i = capacity in MW regarded as the deterministic nameplate rating of the i-th resource not on maintenance

$\tilde{FO}_i$ = forced outage in MW of the i-th source regarded as a random variable

N = the number of sources on the system

The bases behind Baleriaux-Booth theory are the expression of load as a probability distribution function and the convolution of the distribution of the forced outage random variable with the distribution of the load random variable. The convolution of the distribution of the sources guarantees that all the possible combinations of outages are considered.

The LOLP calculation requires that in comparing the output of all the sources with the load at each hour, one must consider all combinations of outages. If the total output of the sources is less than the load, the probability of the event is the loss of load probability. If one weights this LOLP with the weight of the hour with respect to the interval and sums over all the hours, one gets the identical result as that derived from the Baleriaux-Booth procedure.

The use of a simple example will demonstrate the equivalency.

Table I. Assumptions for the Example

Hour	Load MW	Machine	Nameplate Cap MW	Prob. of Outage
1	50	1	40	.20
2	50	2	70	.20
3	50			
4	100			
5	100			
6	100			

Table II. LOLP Calculations

Hour	Machine States (In/Out)	Prob. of Loss of Load
1	Machine 1 in any state; 2 out	1 x .2 = .2
2	Machine 1 in any state; 2 out	1 x .2 = .2
3	Machine 1 in any state; 2 out	1 x .2 = .2
4	Machine 1 and/or 2 out	$1 - (.8)^2 = .36$
5	Machine 1 and/or 2 out	$1 - (.8)^2 = .36$
6	Machine 1 and/or 2 out	$1 - (.8)^2 = .36$
		1.68

Weighted LOLP = 3(1/6 x .2) + 3(1/6 x .36) =
= .28

The logic behind the loss-of-load probabilities is given below. For hours 1 through 3, machine 2 is essential in carrying the load. Machine 1 cannot carry the load by itself and hence its state is immaterial. A failure to carry load is then described by: machine 1 is on and machine 2 is off (.8 x .2) or machine 1 is out and machine 2 is out (.2 x .2). Hence the calculation can be given as 1 x .2. For hours 4 through 6, machine 1 and 2 are both necessary to carry load. Failure to meet load is then 1 minus the probability of both machines being in the on-state.

A standard LOLP calculation would not weight the LOLP values by the hourly weight but would add up the LOLP values for each value to arrive at the expected number of hours, which is 1.68 hours in this example. However, it is easier to show the equivalency with the weighted value since one reads a probability number and not an expected value from a LDC.

Table III. (a) Pr [Load > L] for original LDC
(b) Pr [Load + Outage > L] for convolved LDC

(a)

L in MW	Pr [Load > L]
0	1.00
50	.50
100	0.0

(b)

L in MW	Pr [Load + Outage > L]
0	1.00
50	.68
90	.60
100	.28
120	.20
140	.12
160	.10
170	.02
210	0.0

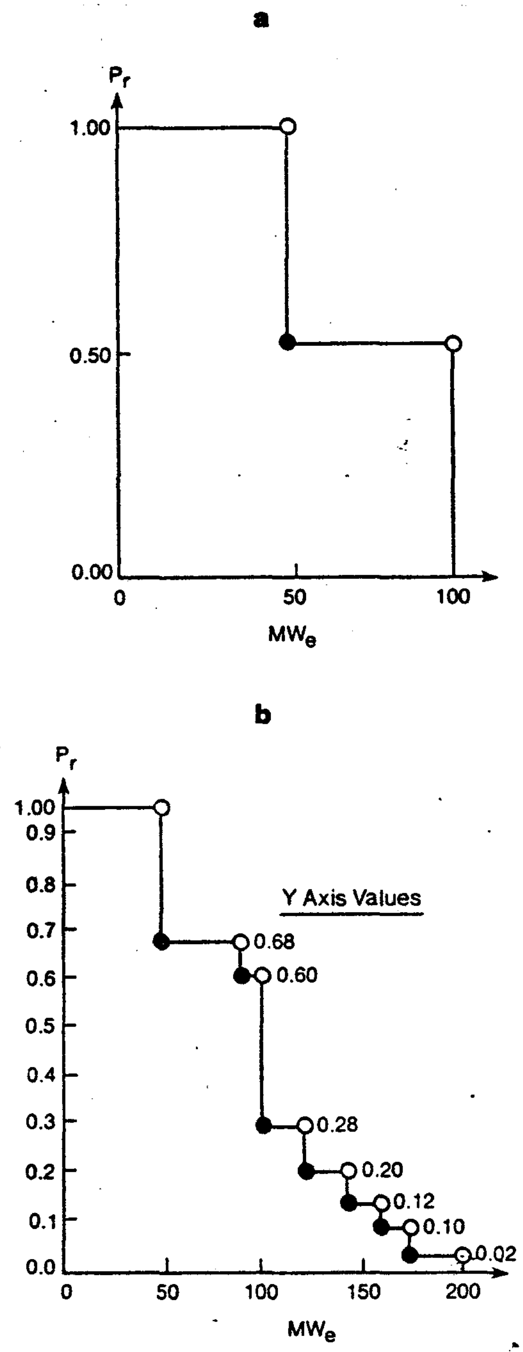

Figure 1. (a) Original Load Duration Curve

(b) Load Duration Curve after the Two Convolutions

The values in the (b) part of Table III may be obtained from the recursive formula for two-state availability

$$F_N(P) = P_N F_{N-1}(P) + (1-P_N) F_{N-1}(P-C_N)$$

where:

F_N is probability distribution after the distribution of the N-th machine has been convolved with F_{N-1}

P_N is the probability of the N-th machine being available

C_N is the capacity for the N-th machine.

However, for such a simple example one can approach the calculation on an intuitive level. To have the capacity of load and the outages sum to less than or equal to 50 MW, the load must be less than or equal to 50 MW and both machines must be available (.5 x .8 x .8 = .32. Hence the entry in the table is 1 −.32 = .68. To have load and outage sum to a value between 50MW and 90MW, the load must be less than or equal to 50MW, machine 1 must be out, and machine 2 must be available (.5 x .2 x .8 = .08). Hence the entry in the table is .68 − .08 = .60. One can continue through the table matching the physical event with the value in the first column. Sophisticated techniques are called for in more complex situations, but the value of this example is its simplistic form.

From Table III and Figure 1, one sees that for a capacity of 110 MW_e, which is the combined capacity for the two machines, the failure to meet load has a probability of 0.28; if one multiplies this by the time under consideration, 6 hours, one gets the expected number for the hours of loss of load.

The Correlation Between Load and Intermittent Energy

Let us now assume a wind machine with 100 per cent reliability and the energy from a wind regime as given in Table IV.

Table IV. Hourly Load and Wind Energy

Hour	Load MWe	Wind Energy MWH	(Load-Wind) MWe
1	50	20	30
2	50	20	30
3	50	20	30
4	100	0	100
5	100	0	100
6	100	0	100

For the moment we will assume that the wind energy is not intermittent but rather remains constant over the hour. We are also assuming that the load is constant over the hour. Hence we have equivalent values albeit different dimensions for energy and capacity. The last column is the difference of the capacities. With this assumption, we will contrast the construction of a load duration curve (LDC) by means of an hourly construction with that in which energy is given a distribution which has been built up over the entire six hour period.

It is common for production costing purposes to form the LDC for the difference of (LOAD - Wind Capacity). If one subtracts the wind capacity on an hourly basis and forms an LDC, one gets the LDC shown in (a) of Figure 2. However, if one treats each of the two distributions of load and wind capacity as independent distributions with the description given in Table V, one gets the LDC in (b) of Figure 2.

Table V: Distributions for Load and Wind Capacity over the Six Hour Period

L in MW_e	Pr [Load > L]
0	1.00
50	.50
100	0.0

L in MW_e	Pr [Wind > L]
0	.50
20	0.0

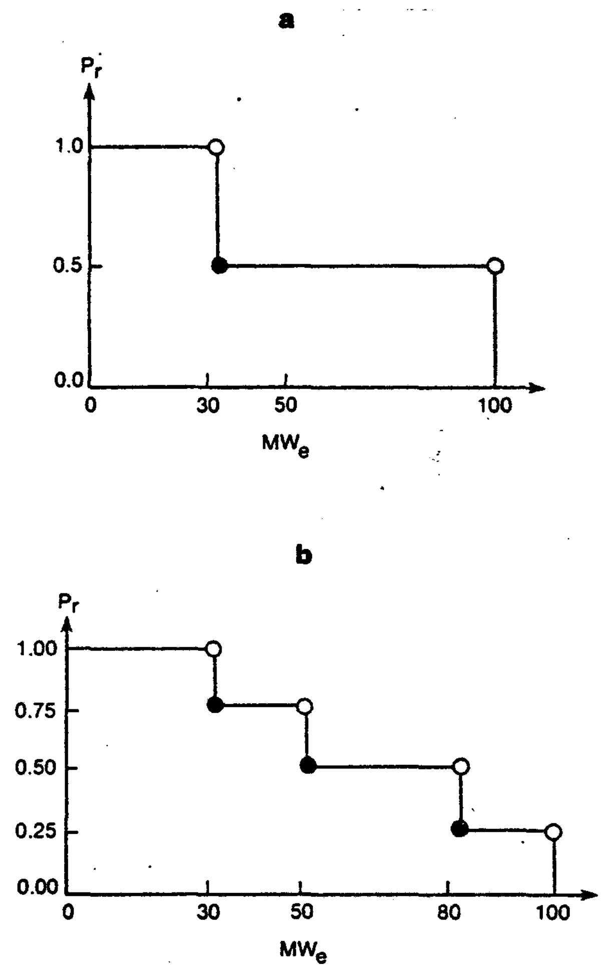

Figure 2. (a) LDC of Load - Wind Energy Subtracted on an Hourly Basis

(b) LDC of Load - Wind Energy with Distributions Treated as Independent.

One should note that the expected capacity demand under both the LDC's in Figure 2 are equal, i.e., E [Load − Wind Capacity] = 65 MW_e. However the load shapes are quite different; in fact, if one assumes that the machine from Table I with capacity 40 MW_e is loaded first, its expected energy output over the six hour period in (a) is 168 MWh [(30 MW x 1.0 + 10 x .5) x .80 x 6 hr] while in (b) the expected energy is 180 MWh [(30 MW x 1.0 + 10 x .75) x .80 x 6 hr]. It is obvious that costs and reliability measures will be different in the two cases; hence it is essential to decide which method is the more representative one.

If the energy from an intermittent source has a distribution which is independent of the time of day then it is legitimate to convolve the two distributions without consideration of the time of day as was done in (b) of Figure 2. However, if the energy output is a function of time of day, taking the difference in hourly values is the correct procedure.

In this particular example the LDC in (b) would call for a different generation mix than the one in (a). The variety in the load shape would be met by machines which would be more efficient and less costly over the different levels of demand. The two-state demand level in (a) presents simpler planning problems. However, one should not read too much into the present phenomenon; the shapes are a function of the assumed data. Still one can make the generalization that there will always be more demand states under the independent assumption. This is true since a single wind capacity value will be subtracted from all load levels in the convolution. In the hour-by-hour case, a single wind value will be subtracted from a single load value. The implication is that there is more involved in choosing the representative procedure than a reliability calculation; the optimum mix is a function of the choice.

In some of the studies which have considered intermittent energy sources, there has been great care taken to show that there is little correlation between load and intermittent energy in the regions studied [2,3]. What has been shown in these studies is that there is no interrelationship between increasing load and diminishing or increasing intermittent energy in the regions studied. The concept being investigated is whether load goes up as a resource such as wind velocity goes down as might occur in a hot climate or whether load goes up as a resource like wind velocity goes up as might occur in a cold climate. However, it is not this concept of correlation in a directional sense which is at question here. For a resource like wind or solar it is the time of day which is important. As an example, wind energy is highly dependent on the warming and cooling of the land [5]. Since the warming and cooling hours occur at a reasonably predictable time of day, the energy at that time of day is correlated to the load demand at the same hour. The amount of demand is also predictable if one knows the system's chronological load shape.

By way of explanation consider the data in Table VI.

Table VI. Time of Day Loads and Wind Velocity

Hour	Load MW_e	Velocity m/s
1	10	2
2	6	6
3	2	2

Let us assume that the table represents a static situation, i.e., that at the first hour of every day the load will be a constant 10 MW_e and the wind velocity will be a constant 2 m/s for the full hour. The Table implies that there is a relationship between 10 MW_e and 2 m/s, between 6 MW_e and 6 m/s, and between 2 MW_e and 2 m/s. The correlation is traceable through the time of day and, for each hour in this example, the relationship is deterministic. However, across the three hours, if one tries to find a relationship like rising/falling or rising/rising, the correlation coefficient is zero.

It is this time of day correlation which forces one to subtract the energy of the intermittent source from the load on a hourly basis. If this time of day correlation is not true, one can treat the intermittent source as any other source in a Baleriaux-Booth code. There would be no need to subtract energy but rather the standard (Load - (CAP - FO)) equation would work if a sufficient number of availability states are input to adequately model the resource. For an uncorrelated type of resource, the accuracy of the reliability measure depends on the number of availability states and the step-size of the code. However, when correlation exists in the specialized sense we are using here, then time of day relationships must be retained and, as will be shown below, problems arise with the reliability measure due to the hourly input.

Let us consider a source in a more realistic wind profile which will give intermittent or variable energy output over each hour. The problem is that the usual input to a Baleriaux-Booth production cost model is a single value for wind energy. This single value must be subtracted from the hourly load. The following example will show that an expected value for the wind energy will not give the correct loss of load probability.

In the example let us assume that a wind regime is such that a constant output is available for the quarter hour periods so that capacity and energy have equivalent values and that wind energy is the only energy to be considered. Let us also assume that the load is constant over the entire hour. Table VII presents such data.

Table VII. Hourly Load and Wind Energy Data

Time	Load MW_e	MW_e	Max {0, Load - Energy}
:15	5	0	5
:30	5	8	0
:45	5	20	0
1:00	5	32	0
1:15	10	0	10
1:30	10	8	2
1:45	10	20	0
2:00	10	32	0
2:15	15	0	15
2:30	15	8	7
2:45	15	20	0
3:00	15	32	0

The problem with trying to input hourly data is immediately apparent. If one calculates the expected wind capacity for any hour, one gets 15 MW_e. Moreover, if there is a reason to believe that time of day correlation exists and hence the hourly relationship must be maintained, then subtraction of expected hourly wind capacity from load gives a zero load for each hour and hence a zero loss of load probability.

However, if one attempts a standard loss of load calculation using the availability states for wind capacity as 0, 8, 20, 32, each with probability of 1/4, one gets the weighted LOLP of 5/12 (1/3 hrs x 5 hrs x 1/4) and the expected loss of load hours of 5/4 (3 hrs x 5/12). (Note: There are 5 quarter hours in which the wind capacity does not cover the load.)

Due to the extreme values used in this example, it is apparent that neither the reliability value nor any production cost values which would be derived from a Baleriaux-Booth code would be very good approximations if one used the expected hourly values as inputs. However, in a less extreme case than given in this example when one uses a Baleriaux-Booth code, it seems likely that the production cost value might possess a better degree of approximation than the reliability figure. This is merely another way of saying that for small penetrations of intermittent resources, the expected hourly energy might do an adequate job in estimating production costs. However, more than production costs are usually desired. It is important to be able to calculate the total value of the intermittent source. This value consists of production cost savings and capacity credit.

Capacity credit in this context refers to the capital costs which are saved by installing an intermittent resource on a system for a fixed level of reliability; the savings may take the form of savings in reduced interest charges, from the costs of plants deferred by the new installations and/or the substitution of less costly plants as dictated from a reoptimization of future expansion. The method of arriving at this capacity credit is usually achieved through equating LOLP values for different schedules of sources [2,4,6]. For the determination of LOLP the example above shows that hourly expected value of energy is inadequate. However, if one uses an hourly availability distribution for the intermittent source in the LOLP calculation the LOLP method will lead to an adequate measure. This method, of course, is nothing more than using various levels of availability over the hour interval [3,5].

In summary one method of handling small penetrations of an intermittent source is to use a Baleriaux-Booth code to calculate production costs. Average hourly wind energy is subtracted from the hourly load. The capacity credit is calculated by means of a LOLP using an hourly availability distribution for the intermittent source. The hourly availability could of course be subtracted from the load in the LOLP as long as all availability states with concomitant probabilities are considered. The problem of course is getting the necessary data in order to arrive at the distribution. A suggested solution for this problem is given below.

However, the solution which we would recommend for the reliability and accompanying capacity credit problem is to make direct use of the Baleriaux-Booth codes. As an introduction to this solution, consider running "scenarios", using a different level of available energy from the intermittent source. One could then weight the loss of load probability according to the probability of the level. The problem here is that one is in danger of choosing all the worst "cases" across all hours, and then moving through the scenarios until all the best "cases" are treated [6]. The process would not be exhaustive and quite inefficient with regard to computer usage. This method does, however, suggest a more accurate procedure using Baleriaux-Booth theory.

Using once again the data of Table VII, one can order the quarter hour data in the last column and form a LDC. It is merely an arbitrary convention of most Baleriaux-Booth codes to accept data in hourly fashion. The theory really desires a continuous flow of input values; the normalization with regard to time is not dependent upon the size of the time mesh used for the inputs. So quarter hour inputs, or more generally, any orderable inputs with the proper probability values will do. The resulting LDC is given in Figure 3.

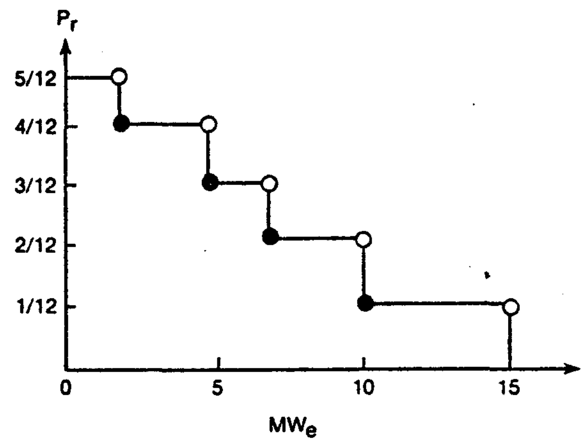

Figure 3. The LDC Based on the Last Column of Table VII

Since we have assumed in this example that only wind energy is to be considered and since the intermittent sources have been included via subtraction, one reads the loss of load probability at 0 MW_e, i.e., 5/12. The expected loss of load hours is 5/4 (5/12 x 3 hrs). These values, of course, are the same as those derived in the LOLP calculation done earlier. Therefore what is needed to make the usual Baleriaux-Booth codes work in this situation is a preprocessor for the data which considers the hourly distribution of intermittent energy, does the subtraction, orders the data according to magnitude, and then chooses data points in a manner consistent with standard input requirements [1,5]. All chronology is lost; chronology, of course, is not necessary for a production cost approximation but some method of restoring chronology is needed if one desires marginal cost estimates. At this time we would recommend the creation and storage of a matrix whose function would be to trace the original hours based on the new LDC inputs.

We have been assuming an intermittent source with 100 per cent reliability. This restriction can be easily removed. What is required is to calculate correctly the probability of each level of availability. For the zero output one must sum the probability of zero wind energy and the product of the probability of non-zero wind energy and the forced outage rate. For the non-zero levels, we need the product of the probability of the level of availability and the probability of being on-line (1 minus forced outage rate).

The purpose of this paper has been to present a methodology to approximate with a fair degree of accuracy the effects of a source which may provide a range from zero output to maximum output, possibly more than once, during the interval of an hour. The reader is perhaps aware that the data for these sources is quite often available only in the form of an hourly observation. With this data the distribution profile is lost. With data in the form of an hourly average, the chance of a zero value over the hour is lowered [7]. This paper has pointed out the effect of this type of data on the reliability measures. In the case of a wind resource one can restore the distribution profile from the average value of the wind velocity.

Ideally if one has multiple years of data, one could reassemble an hourly profile. Lacking this data one could fall back on one of the descriptive distributions which are being suggested in the literature. The Weibull or Rayleigh and the Beta distributions are common ones. One might even consider mixing a discrete weight at a velocity below cut out with one of these continuous distributions. By using estimators for the mean and variance of these distributions, a histogram of wind velocity for each hour could be produced. The histogram can include as many "bins" as the planner believes necessary. This method will produce the various levels of availability with their concomitant probabilities. Unfortunately, we are only aware of descriptive distributions for wind energy; for other intermittent sources the "fitting" distributions are not commonly found in the literature. However, as the resources move closer to commercial feasiblity, we can be certain that their output profiles will be better described. We would also like to emphasize that the "fitting" distribution is no substitute for good data. The better the data, the easier it is to build profiles or to make estimates of the distribution parameters.

We would like to close with comments on some of the problems remaining in system source modeling in general and in Baleriaux-Booth modeling in particular. For large penetrations of intermittent sources, the control problems for system stability are not adequately understood. There are the problems of feasibility of large penetration, cost penalties for the up and down behavior of backup resources with any penetration, possible reallocation of hydro resources, and spinning reserve requirements. There is the problem of actual response time of conventional sources, as the time increment for the intermittent source decreases below that of an hour, the response of replacement energy may not be quick enough for load following. With regard to the Baleriaux-Booth models, the sequential time correlation of the energy from intermittent resources is in danger of being ignored. The output from consecutive hours is correlated and if one uses the hourly averages from a particular year to build distributions, this correlation will be modeled. However, as hourly data from various years are built up, the relationship between distributions from consecutive hours may be lost. However, this loss of hourly correlation may be irremedial in the Baleriaux-Booth model; we see the same phenomenom in the duration aspect of forced outages for conventional sources.

CONCLUSIONS

The use of an average value for an intermittent resource does not give an accurate estimate of the utility system loss-of-load probability or production costs. Therefore, any capacity credit established for the intermittent resource will be in error. The use of a probability distribution over the capacity from the intermittent source will give an improved approximation and is compatible with the theory of Baleriaux-Booth production cost models.

The methodology outlined in this paper is the starting point in an on-going process. The next step is to investigate the formation of daily wind energy profiles. If the construction of common daily profiles, consisting of distributions dependent on time of day and on season of the year, can be constructed for specific sites and/or regions, then system generation modeling can be greatly facilitated. Following the characterization of wind energy, a comparison of the method described in this paper with those of previous studies will be carried out to see the effects of the more accurate modeling endeavor. Finally a comparison of predicted results with the operational data from a system-connected machine will be made in order to establish what further conceptual changes must be effected in order to model more accurately the intermittent resources.

ACKNOWLEDGEMENT

The authors wish to thank Drs. Tom Reddoch, Gerry Park, Peter Moretti, Jeff Rumbaugh, and Robert Sullivan for their motivational comments on this topic.

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