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Calculating the Capacity Credit of Wind Power

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SUMMARY The value of wind power as firm capacity in an electricity grid without storage is investigated, primarily by means of a numerical probabilistic model. The magnitude of wind power capacity credit is usually found to be greater than 40 percent of the capacity credit of a typical conventional unit with the same average power output. For very small values of wind power penetration into the grid, the two measures of capacity credit utilised are each approximately equal to the average wind power, while for large penetrations the measures approach different constant values. The behaviour at both limits is in good agreement with the results of an analytic probabilistic model. The results are also compared with those from an hour by hour computer simulation.

It is found that wind power capacity credit is very sensitive to the penetration of wind power into the grid, to the unit sizes of the conventional plant in the grid and to the start up speed of the aerogenerators. The credit is moderately sensitive to the replacement of the load distribution by a Gaussian distribution, to the forced outage rate of conventional plant, to the wind speed distribution and to the magnitude of the loss of load probability in the absence of wind power plant. The credit is found to be insensitive to the rated speed of the aerogenerators (given the same average wind power output).

NOTATION

a_i	parameter expressing the variation of LOLP with additional firm capacity
A	available power (MW) at a given time
C_F	equivalent firm capacity (EFC)
C_L	effective load carrying capability (ELCC)
EFC	Equivalent Firm Capacity, a measure of capacity credit of non-firm plant (in MW)
ELCC	Effective Load Carrying Capability, a measure of capacity credit of non-firm plant (in MW)
f	capacity factor $\bar{W}/W_r$
f.o.r.	forced outage rate of a conventional unit (fraction of hours per year)
L	load or demand on the grid (MW) at a given time
$\bar{L}$	mean load
LOLP	loss of load probability
p_0	loss of load probability (LOLP) of original grid (zero windpower capacity)
p_F	LOLP after hypothetical firm capacity C_F has been added to the original grid
p_W	LOLP after non-firm capacity W_r has been added to the original grid
Pr	probability
R	ratio $v_r/\bar{v}$ of wind speeds
$\bar{v}$	annual mean wind speed at aerogenerator site
v_f	furling wind speed of aerogenerators
v_r	rated wind speed of aerogenerators
v_s	start up speed of aerogenerators
W	available power (MW) at a given time of non-firm plant (wind or conventional) which is added to the original grid
$\bar{W}$	mean value of W
W_r	rated capacity of non-firm plant (wind or conventional) which is added to the original grid
WA	Western Australia
x	parameter for scaling results to different sized grids

1 INTRODUCTION

At the Second International Symposium of Wind Energy Systems, it was stated in one paper that "Introduction of wind turbines into the existing [grid] system does not lead to savings with regard to the necessary power to be installed in the form of conventional plant" (Bontius et al., 1978). However, the preceding paper at the same Symposium presented a model in which wind power displaced conventional capacity and hence saved capital as well as fuel (Johanson and Goldenblatt, 1978). More recent work indicates that capacity credit of wind power is a function of many system parameters, especially the degree of penetration of wind power into the grid (Kahn, 1978; EPRI, 1979).

In this paper, we attempt to resolve the controversy by setting up a numerical probabilistic model to evaluate capacity credit as a function of wind penetration and by testing its sensitivity to several system parameters. We utilise as a basic electricity grid without storage that of Western Australia in the year 1978, and investigate quite a number of variants of it. Two measures of capacity credit are considered: the Equivalent Firm Capacity (EFC) and the Effective Load Carrying Capability (ELCC). Capacity credit as a function of wind power penetration is obtained for different values of the reliability of the grid as measured by the loss of load probability (LOLP), the composition of the grid, forced outage rates of conventional plant, aerogenerator response characteristics, etc.

The model's results are compared with (i) the results of an hour by hour computer simulation, an approach which is very expensive in computer time, and (ii) the results of an analytic probabilistic model of Haslett and Diesendorf (1980). All three methods are found to yield qualitatively similar results, and in certain parameter domains there is good quantitative agreement between the analytic model and the numerical probabilistic model. But before the models are described and the results presented, some basic concepts are required.

2 BASIC CONCEPTS

An electricity grid has a total installed conventional generating capacity C, of which a capacity A is available (i.e. not undergoing scheduled or forced outages) at a given time. The load or demand at a given time is L. Figure 1 gives diurnal load curves for typical winter and summer days in the WA grid. The loss of load probability (LOLP), denoted by p_0, is the fraction of time the available power A is less than the load L:

$$p_0 = \Pr(A < L), \tag{1}$$

where both A and L are random variables. In this paper we only consider the LOLP arising from breakdowns in generating plant; the relatively large contributions from transmission and distribution outages and the contribution from strikes are not considered. As a planning criterion, a value of p_0 in the range 10^{-3} to 10^{-5} is typical; often this is expressed as e.g. 'one hour in one year' (i.e. $p_0=1/8760$) or something similar.

If a certain amount C_F of hypothetical firm capacity (forced outage rate=0) is added to the grid, LOLP is reduced to p_F, where

$$p_F = \Pr(A + C_F < L). \tag{2}$$

Alternatively, if non-firm capacity of rated power W_r (of which a capacity W will be available at a given time) is added to the original grid specified by (1), LOLP becomes

$$p_W = \Pr(A + W < L). \tag{3}$$

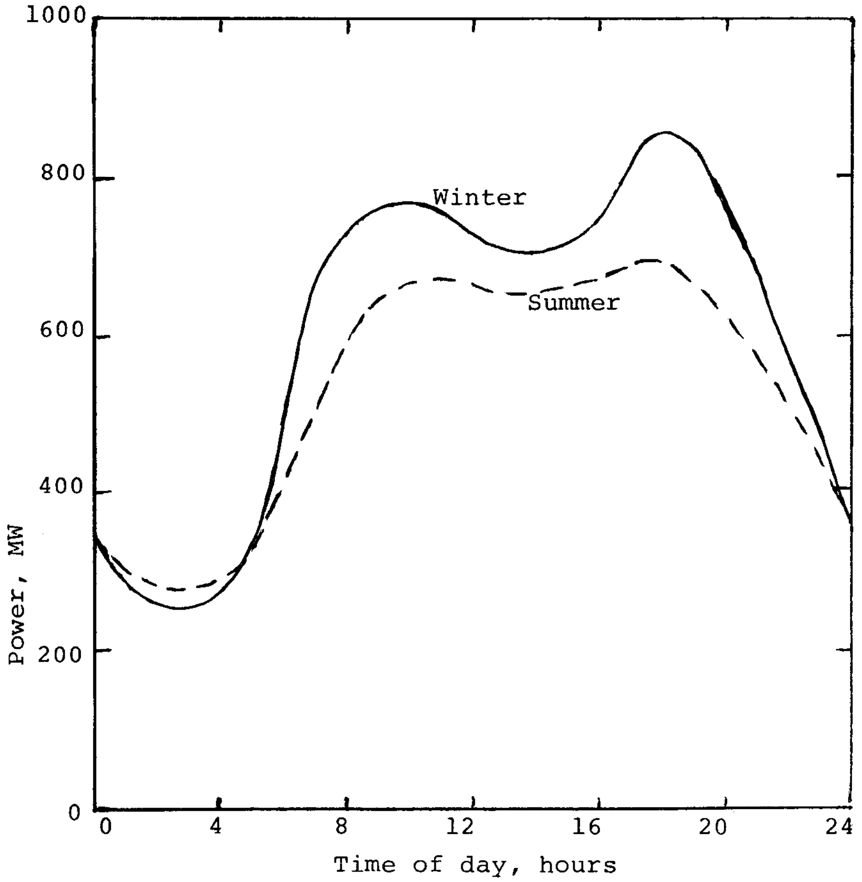

Figure 1. Diurnal load distributions for typical summer and winter days in the WA grid.

The Equivalent Firm Capacity (EFC) of the non-firm capacity W_r is then defined to be the value of C_F obtained by equating p_F and p_W from (2) and (3). Clearly, EFC may be calculated for conventional as well as for wind power plant; in the former case forced outages are due to breakdowns while in the latter they are mainly due to lulls in the wind.

A second, better known measure of capacity credit is the Effective Load Carrying Capability (ELCC) (e.g. see EPRI, 1979). If non-firm capacity W is added to the grid, ELCC is the value of a hypothetical firm load C_L (variance of C_L =0) added to L such that

$$p_0 = \Pr(A + W < L + C_L). \tag{4}$$

In other words, ELCC is the amount by which the load may be increased in the presence of additional non-firm capacity while the original LOLP of p_0 is maintained.

To permit the comparison of the capacity credit of wind power and conventional plant, it is useful to express EFC and ELCC in terms of the average rather than the rated capacities of non-firm plant. In the case of wind power plant,

$$W_r = \overline{W}/f, \qquad (5)$$

where $\overline{W}$ is the mean wind power output and f is the capacity factor of the system of aerogenerators which is determined primarily by the choice of the ratio $R=v_r/\overline{v}$ (Diesendorf and Fulford, 1979). These definitions of capacity credit and two additional ones are discussed in more detail by Haslett and Diesendorf (1980).

The probability distribution of available wind power is a filtering of the wind speed distribution by the aerogenerator characteristics. Our 'standard' aerogenerators have $v_s=4ms^{-1}$, a simple cubic power response up to $v_r=15ms^{-1}$ and a constant response from there to $v_f=40ms^{-1}$. All wind speeds are measured at hub height. The aerogenerators are sited in a region with a spatially homogeneous Rayleigh distribution of wind speeds with $\overline{v}=7.5ms^{-1}$, and hence $R=v_r/\overline{v}=2$.

3 THE MODELS

3.1 Numerical Probabilistic Model

In this model, a mesh (e.g. 2MW intervals for a grid of total rated capacity of order 1000MW) is established and LOLP is calculated numerically, direct from the probability distributions of load, available conventional capacity and wind power.

The basic grid used is a particular configuration which represents approximately the Western Australian (WA) grid in the year 1978 (Table 1).

TABLE 1. Conventional units in the basic electricity grid which is an approximate representation of the WA grid in 1978. Other grid data: $C=1220MW$, $p_0=8.2 \times 10^{-4}$, $\overline{L}=513MW$, record load=991MW, standard deviation of load=169MW.

Station	Number of units	Rated capacity (MW)	Forced outage rate
1	10	30	0.08
2	4	60	0.08
3	4	120	0.08
4	1	200	0.08

The probability distribution of load is obtained from half-hourly averaged load data for WA in the period 1970-1979. Because the mean of the load increased approximately linearly in this period, we have rescaled all load values to the 1978 mean.

The probability distribution of available conventional capacity is calculated from the forced outage rates of the individual units, and takes into account all combinations of simultaneous forced outages. It is assumed here that scheduled outages do not contribute to LOLP.

Firm capacity is incorporated in the model by appropriately shifting the distribution of the available conventional capacity. For calculating EFC, a set of LOLPs p_0, p_{F_1}, p_{F_2},... is obtained from (1) and (2). By taking the value p_W and interpolating within this set, a corresponding value of C_F can be determined. Empirically it is found to a good approximation that

$$p_{F_i} \simeq p_{F_{i-1}} \exp(a_i(C_{F_i} - C_{F_{i-1}})), \qquad (6)$$

where the a_i vary slowly when $C_{F_i} - C_{F_{i-1}} \lesssim 10MW$, so the interpolation procedure can be made accurate. A similar procedure is used to obtain ELCC.

The major advantage of the numerical probabilistic model is its use of realistic loads and the relative ease of obtaining diverse numerical results.

3.2 Simulation Model

A simulation model, used mainly to obtain information about fuel savings and grid operating strategies in the presence of wind capacity, has also been used to derive estimates of capacity credit as measured by EFC. The model is discussed more fully in Diesendorf and Martin (1979, 1980). It uses as input real hour by hour load and wind data, and specifies for the conventional units their individual capacities, forced outage rates, start up times, etc. At each time step, an algorithm is used to decide which units are to be turned on or off; the decision is made on the basis of previous loads and wind power, and other factors.

To adapt the simulation model to calculate estimates of capacity credit, small units of firm capacity were added to the grid at the bottom of the merit order, and the numbers of times these were fired up was recorded. These results were then compared to a simulation in which wind power capacity was added to the conventional grid, and an estimate of the EFC thereby obtained. To obtain reasonable numbers of loss of load events (which normally occur only a few times per year of simulation), the model was set up to simulate repeatedly the particular week with the year's highest load, with forced outages determined randomly.

The advantage of the simulation model is its inclusion of the dynamical response of the grid system to outages and changes in wind speed. Its disadvantages are the very large computational effort required and the fact that the results are samples drawn from a distribution rather than expectation values, and hence that accurate results require an extended calculation.

3.3 Analytic Probabilistic Model

Haslett and Diesendorf (1980) present an analytic model for calculating capacity credit, based on the following assumptions:
(i) load has a Gaussian distribution;
(ii) available conventional capacity has a Gaussian distribution;
(iii) there are no correlations between load, available plant and wind power;
(iv) the original conventional units in the grid are identical.

The basic approach in this model is to replace A and L in (1) by Gaussian distribution functions; p_0 then becomes an integral. Because C_F has no variance, its addition in (2) merely shifts the mean of the distribution A, giving a new expression for p_F. Equating the expression for p_F and p_W then gives an implicit expression for C_F as a function of the added non-firm capacity W_r, which may be solved readily.

In this way, expressions for capacity credit as a function of wind penetration, forced outage rate, coefficient of variation of wind power, and other parameters, have been obtained. In the limits of very small and of very large wind penetrations, the expressions yield simple analytic results, to which more realistic computer model results may be compared. The main limitations of the model are assumptions (ii) and (iv).

4 RESULTS

In the following subsections, we present results for the capacity credit of wind power as a function of wind penetration into the grid, for different values of LOLP, grid composition, aerogenerator characteristics and several other parameters. Tables 2, 3 and 4 demonstrate first and foremost the strong characteristic dependence of the magnitudes of wind power capacity credit on penetration of wind power into the grid. The magnitude of the credit is usually a substantial fraction of the mean wind power output for penetrations $\overline{W}/\overline{L}$ up to about 25 percent. For conciseness we have omitted most of the numerical results obtained for ELCC; in most cases the ratio of ELCC to EFC is the same as for the standard case in Table 2.

TABLE 2. Capacity credit as a function of wind penetration obtained from the numerical probabilistic model for different grid and wind characteristics. Units are in MW. For columns 3 to 9, except when specified otherwise, the grid and load are as given in Table 1, and a Rayleigh wind speed distribution is assumed. In the last four columns the capacity of each unit in Table 1 has been multiplied by the number in parentheses, to change p_0 (column 6) or to return p_0 to approximately 8.2×10^{-4} (columns 7 to 9).

Rated wind power W_r	Mean wind power $\overline{W}$	EFC	ELCC	real wind EFC	p_0= $5.5x10^{-5}$ (1.2) EFC	Gaussian load (1.067) EFC	f.o.r.= 0.04 (0.9) EFC	f.o.r.= 0.16 (1.267) EFC
50	10.7	9.5	9.6	9.3	9.4	9.6	9.0	9.6
100	21.4	16.6	16.9	16.2	16.5	17.1	15.7	17.4
180	38.5	25.4	25.9	24.7	25.1	26.6	24.0	27.2
300	64.1	34.8	35.6	33.8	34.0	36.8	32.8	37.8
500	107	45.4	47.0	43.5	44.3	48.7	42.0	50.2
800	171	55.9	58.5	53.0	54.6	60.6	51.0	62.7
1200	256	64.9	68.8	61.1	63.0	71.0	58.8	73.6
2000	427	74.9	80.9	69.3	72.0	83.2	66.9	86.5
5000	1070	86.2	96.2	76.3	82.7	97.9	75.0	103
20000	4270	88.6	100	77.2	84.7	102	76.4	107

TABLE 3. Capacity credit as a function of wind penetration obtained from the numerical probabilistic model for different grid compositions. Units are in MW and all credits are EFC. Total capacity is adjusted to achieve a constant p_0= $8.2x10^{-4}$. Load is specified in Table 1 and a Rayleigh wind speed distribution is assumed. In the 530x2MW column the Poisson distribution is used for calculating availability.

Rated wind power W_r	Mean wind power $\overline{W}$	Table 1 grid	530x 2MW units	15x 77MW units	7x 200MW units
50	10.7	9.5	8.9	8.9	9.6
100	21.4	16.6	14.2	16.1	18.8
180	38.5	25.4	19.6	24.3	30.0
300	64.1	34.8	24.2	32.5	41.8
500	107	45.4	28.9	42.4	55.7
800	171	55.9	32.8	51.9	70.5
1200	256	64.9	35.5	59.6	83.6
2000	427	74.9	37.6	67.6	100
5000	1070	86.2	38.5	74.7	121
20000	4270	88.6	38.5	75.7	127

TABLE 4. Capacity credit as a function of wind penetration for different aerogenerator characteristics. Units are in MW and grid and load characteristics are given in Table 1. $\overline{v}$=7.5ms^{-1} for both values of R. (For a given W_r, there is a slight difference in $\overline{W}$ for the different values of v_s; $\overline{W}$ values listed are for v_s=4ms^{-1}.) All credits are EFC.

	R=2 (v_r=15ms^{-1})			R=1.5 (v_r=11.25ms^{-1})		
W_r	$\overline{W}$	v_s= 4ms^{-1}	v_s= 6ms^{-1}	$\overline{W}$	v_s= 4ms^{-1}	v_s= 6ms^{-1}
50	10.7	9.5	9.0	19.2	16.5	15.4
100	21.4	16.6	15.6	38.4	28.7	26.0
180	38.5	25.4	23.4	69.0	41.6	36.3
300	64.1	34.8	31.3	115	53.2	43.7
500	107	45.4	39.1	192	64.6	48.8
800	171	55.9	45.0	307	74.0	51.2
1200	256	64.9	48.8	460	80.4	52.0
2000	427	74.9	51.4	767	85.8	52.2
5000	1070	86.2	52.2	1920	88.5	52.2
20000	4270	88.6	52.2	7670	88.6	52.2

To scale the results of the capacity credit calculations to a grid with mean available power x times larger than that of our reference grid, one simply multiplies all the quantities measured in units of electrical power - load, unit sizes, wind power capacity and capacity credits - by x.

4.1 Wind Power Penetration

Figure 2 and Table 2 (columns 1 to 4) give EFC and ELCC as functions of mean wind power $\overline{W}$ for the WA grid, as obtained from the numerical probabilistic model. Real distributions of load and of available conventional capacity, Rayleigh wind and 'standard' aerogenerator characteristics have been utilised.

The form of the curves is insensitive to changes

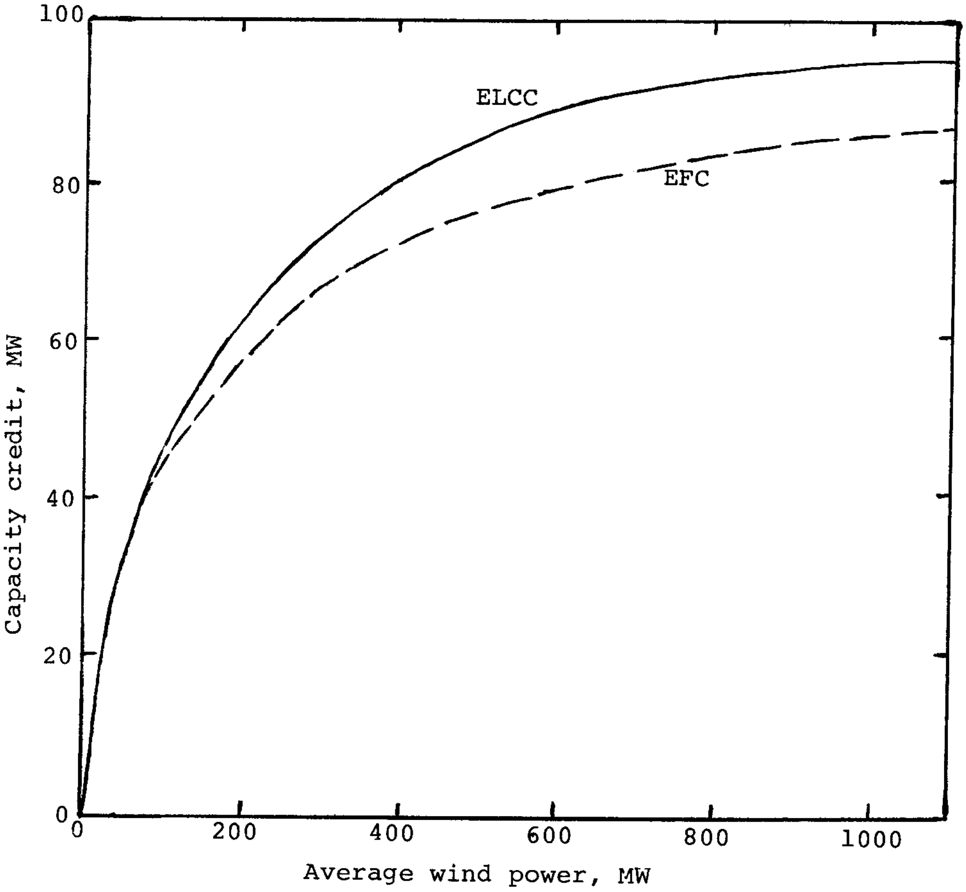

Figure 2. Capacity credit as a function of wind penetration for the WA grid and 'standard' aerogenerator characteristics.

in the other parameters to be discussed below. Several significant features are apparent. At very low penetrations, EFC and ELCC are each approximately equal to $\overline{W}$, as predicted by the analytic model of Haslett and Diesendorf (1980). With increasing penetration, EFC and ELCC drop below $\overline{W}$ and, in the limit of large penetrations, reach constant but differing values. A penetration level $\overline{W}/\overline{L}$ of about 20 to 25 percent is an important reference point because about this level there are rapidly diminishing returns in fuel savings (as a result of wind energy losses) and a rapid increase in the number of start ups of conventional plant required (Sørensen, 1978; Diesendorf and Martin, 1979, 1980). At this penetration level (i.e. $\overline{W}\simeq$100MW in the WA grid), the capacity credit of wind power is approximately equal to 0.4$\overline{W}$.

TABLE 5. Number of loss of load events obtained from the simulation model for the WA grid in the week beginning 23 July 1978, which includes the record peak of 991MW for 1978. The week was simulated 100 times with random failures for conventional plant. Grid composition is similar to Table 1 except that available grid capacity is somewhat reduced to obtain a higher number of loss of load events. Wind data is from Waitpinga, South Australia.

Added capacity, MW	Number of loss of load events
0	29
10 firm	19
20 firm	16
30 firm	6
40 firm	7
60 average wind (250 rated)	7

Results from the simulation model for a wind regime which has no significant correlation with load are compatible with Figure 2. Table 5 lists the number of loss of load events for the conventional grid with various amounts of firm capacity added. It also lists the number of loss of load events occurring when a specified wind power capacity is added to the grid. The wind speeds used were measured at Waitpinga, South Australia, and have little correlation with the WA (or South Australian) daily load distributions. Because the results are samples drawn from a distribution, there are considerable uncertainties. Still, it is apparent that, according to the simulation model in this case, 60MW of average wind power has EFC in the range 25 to 40MW, quite compatible with the expectation value of 33MW obtained from the numerical probabilistic model.

Table 6 lists similar results obtained using wind data from Fremantle, WA. These results show the increase in wind power capacity credit that may result when there are positive correlations between wind power and load. These results suggest an area for future development of the analytic and numerical probabilistic models.

4.2 LOLP

Table 2 also shows the capacity credit of wind power for one other value of p_0. When p_0 is larger, EFC is larger. This result may be understood in terms of the effect of wind power on the

TABLE 6. As Table 5, except that the available grid capacity is altered somewhat further, and the wind data is from Fremantle, WA.

Added capacity, MW	Number of loss of load events
0	141
20 firm	106
40 firm	83
60 firm	64
80 firm	45
100 firm	35
120 firm	24
84 average wind (500 rated)	20

integral of the product of the probability density of load and the cumulative distribution function of available conventional capacity. This integral determines p_0. Wind power added to the grid causes an increase in mean availability of total plant which, due to the variability of wind, results from a spreading of the availability distribution in one direction. In contrast, added firm capacity causes an increase in mean availability by a simple shift in the availability distribution. The increase in availability due to added wind power has a greater effect on p_0 when p_0 itself - the above integral of the product of load and availability - is larger. Similar considerations, though with a smaller numerical effect, apply to conventional plant. These considerations also explain why ELCC is usually larger than EFC: namely, ELCC is calculated in terms of p_0 while EFC is calculated in terms of p_F which is always less than p_0.

A smaller LOLP may be obtained by increasing total capacity, by reducing load peaks, by reducing forced outage rates or by reducing average load. Because of the effect of p_0 on capacity credit, we keep this parameter constant in subsections 4.3 to 4.5 below. This is achieved by adjusting the rated grid capacity (done by multiplying each unit's capacity by a factor such as 0.9 or 1.1), thereby leaving the load distribution unchanged. However, similar results are obtained when a constant p_0 is obtained by changing the load and leaving the grid unchanged.

4.3 Grid Composition

Table 3 shows that capacity credit for wind power is much higher when the conventional grid is composed of a small number of large units as compared to a large number of small units. This again is due to the shape of the availability distribution. When there is a small number of large units, the simultaneous forced outage of even a few units causes a large change in availability: the availability distribution is much broader and flatter. (Consequently, as is apparent in Table 3, the grid capacity must be increased to attain the same p_0.) Hence in this case, wind power, which causes a broadening shift in the availability distribution, has more effect on p_0 than when the integral of the product of load and availability is dominated by a smaller range of load values.

4.4 Aerogenerator Characteristics

Table 4 gives capacity credits for two values of the aerogenerator start up wind speed v_s at a constant rated speed v_r. For small wind penetrations, the difference in capacity credit is small, but for saturation credit the difference is considerable. The results are in agreement with the analytic model which demonstrates that, as wind penetration becomes very large, the capacity credit depends solely on the fraction of time the aerogenerator system produces zero power, and on the value of p_0. Thus, even though the value of the extra energy provided by a lower start up speed is almost negligible, its contribution to capacity credit can be quite significant.

By contrast, the effect of changing the value of $R=v_r/\overline{v}$, when v_s remains constant, is relatively small. For a given average wind power $\overline{W}$, R=1.5 gives EFC and ELCC values very similar to those of Figure 2: slightly higher capacity credits for intermediate penetrations but the same saturation credit. Since, for smaller R, the same average wind power is attained with a smaller rated wind capacity, a given <u>rated</u> wind power has a higher capacity credit for smaller R.

Reducing R below its optimal value of about 2 reduces fuel savings for a turbine with a given swept area (Diesendorf and Fulford, 1979). However, if the start up speed is a fixed fraction of the rated speed (as is often the case: see Allen and Bird, 1977), reducing R will also reduce the start up speed. Thus, in this particular case, there is a trade-off between fuel savings and capacity credit. A decision to choose the value of R for an aerogenerator system must take into account the costs of conventional capacity and fuel as well as wind capacity costs.

4.5 Other Parameters

We summarise here further results from the numerical probabilistic model.

Using the realistic wind speed distribution from Fremantle, WA moderately reduces the wind power capacity credits, especially at high wind power penetration. This conclusion is based on the assumption that correlations between wind power and load are equal to zero.

Replacing the empirical load distribution with a Gaussian distribution having the same mean and variance increases p_0. This is because a major component of the variance in load is due to the typical diurnal load changes (Figure 1) as opposed to random fluctuations (e.g. due to very cold or very hot days). It is primarily the random fluctuations which shape the tail of the load distribution which in turn contributes to p_0. With a Gaussian load distribution, the grid capacity must be increased to maintain the same value of p_0. The wind power capacity credit increases compared with the case of real load, especially at high penetrations where the fractional increase in capacity credit reaches about 15 percent.

Changing the forced outage rate has a moderate effect on EFC and ELCC, once the mean grid capacity is adjusted to recover the same p_0. A lower forced outage rate reduces the capacity credit, owing to the reduction in the spread in the availability distribution, as discussed before.

5 CAPACITY CREDIT OF CONVENTIONAL PLANT

If, instead of wind power plant, we add to the original grid non-firm capacity rated at W_r in the form of a single additional conventional unit, we obtain the values of capacity credit, expressed as a function of the unit's size W_r, given in Table 7. For the same average power output, wind power capacity credit is generally greater than or equal to 40 percent of that of a single additional conventional unit in the WA grid with a forced outage rate of 8 percent.

6 CONCLUSION

We have found that the magnitude of wind power capacity credit is indeed significant and depends strongly upon the degree of penetration of wind power into the grid. In particular, for very small wind power penetrations, capacity credit is approximately equal to the average wind power $\bar{W}$; at a penetration $\bar{W}/\bar{L}$ of about 20 percent, capacity credit is about $0.4\bar{W}$ and at very large penetrations capacity credit approaches a constant value which depends on the probability of zero wind and on p_0.

The numerical probabilistic model is a simple, flexible and economical (of computer time) method of determining the capacity credit of wind power plant and conventional power plant in an electricity grid. Its results are consistent with those from an analytic probabilistic model (Haslett and Diesendorf, 1980) and a limited computer simulation.

The major advantages of using several models are in validating results, in exposing implicit assumptions in the models, in highlighting numerical limitations of the numerical probabilistic model, and in pointing to possibilities for usefully expanding the generality of the analytic and numerical probabilistic models.

We have not investigated in detail the effects on capacity credit of storage, of correlations between wind power and load, of interruptible load, of spatial variations in wind speeds or of peak load limiting policy strategies.

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TABLE 7. Capacity credit of a single conventional unit with f.o.r.=0.08 added to the WA grid in Table 1. Units are in MW.

Rated power W_r	Mean power $\bar{W}$	EFC	ELCC
10	9.2	9.13	9.16
50	46.0	44.1	44.2
100	92.0	81.8	83.5
200	184	125	138
400	368	135	163
1000	920	135	164

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