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Simulation of the Hourly Wind Speeds for Randomly Dispersed Sites

**W. C. Cliff
C. G. Justus
C. E. Elderkin**

May 1978

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FOR RANDOMLY DISPERSED SITES

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SUMMARY

A technique is presented which simulates the hourly wind speeds at any number of dispersed sites within a region. The required input for the simulation is an hourly wind speed record from a single "representative site" and an estimation of the size of the region in which the sites will be located. This technique is not intended for use at any specific location but rather intended to be used for generic mission analysis type studies.

A "representative site" for this study is a site which has an annual mean wind speed representative of the annual mean wind speed at all sites under consideration. With this information, a probability density distribution for the wind speed averaged over all the sites within the region is constructed. The time history of the hourly mean wind speeds from the representative site is then used with a frequency-matching technique to establish the hourly sequence of regional average wind speeds (regional average being the average wind speed from a very large number of potential sites within a region). A Monte Carlo technique is then used to develop the hourly mean wind speeds at any number of desired sites, which are assumed to be randomly distributed throughout the area.

These simulated wind histories may then be used to simulate the hourly time history of the power output of a network of wind turbines located at these random sites, by assuming the desired number and size of wind turbines to be placed at each site. Using the simulated wind speed at each site in conjunction with the wind turbine's operating characteristics, the hourly power for each site is calculated and the calculated power for all sites is then summed to yield the total power produced by the wind turbines for that hour. The power produced at each consecutive hour is computed in the same manner, yielding a simulated time history of the power produced by the wind turbines.

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SIMULATION OF THE HOURLY WIND SPEEDS
FOR RANDOMLY DISPERSED SITES

(For use in the simulation of power produced
by wind turbines located at these sites)

W. C. Cliff, C. G. Justus,
and C. E. Elderkin

INTRODUCTION

It was brought to the attention of Pacific Northwest Laboratory (PNL) that there was a need to have a method by which the output of a single anemometer could be used to simulate the power output of a wind farm with dispersed single machines or multiple machines in groups. Based upon this need, this report provides a technique by which simulated hourly wind speeds at any number of randomly dispersed sites are developed using as input only the hourly wind speed from a single anemometer and the size of region desired.* Using these simulated wind speeds at each site in conjunction with the wind turbine's characteristics, the hourly power for each site is calculated and the calculated power for all sites may then be summed to yield the total power produced by the wind turbine array for that hour. The power produced at each consecutive hour may then be computed in the same manner, resulting in a simulated time history of the power from the wind turbine array.

The model is intended for mission analysis type studies and should not be construed to be a solution to any specific region. Specific locations could require extensive knowledge of topography, exact locations of sites, etc. The model

*The technique presented in this paper may be used for wind speeds representing wind records of length 15 minutes or longer. Wind speeds representing shorter lengths should not be used however. These shorter lengths would include turbulence effects for which this paper is not intended.

developed in this study uses results taken around the United States and does not represent any particular location.

APPROACH

Two basic inputs are required for the model: an estimate of the size of the region considered and a temporal sequence of hourly mean wind speeds from a single representative site. One could potentially use any site for which the annual mean wind speed could be scaled to the mean wind speed of other potential sites within a region. The term "regional average" will be used to define an average taken over all equivalent sites within a region. That is, only sites with the same annual mean would be included in such an average. Similarly, the annual mean wind speed of the simulated sites will statistically have the same annual mean wind speed as the representative site, but this also could be scaled if so desired. In this paper, no scaling will be used but we will point out where it could be used if desired. Note that, in addition to the annual mean, the seasonal and diurnal variations of mean wind speed of the "representative" site are also imposed on the array simulated speeds. Therefore, if accurate modeling of seasonal and diurnal variations are desired, care should be taken to select a representative site whose seasonal and diurnal variations match those desired for the array.

Based upon statistics for the representative site, the size of the region, and equations for the correlation within a region developed by Justus^(1,2) (modified for random spacing about a central site), the probability distribution of the regional average wind speed is developed. By a frequency-matching technique, the temporal sequence of hourly wind speeds for a single site is used to generate a temporal sequence of hourly regional average wind speeds. A formula is then

developed for the probability density distribution of hourly wind speeds as a function of regional size and the hourly regional average wind speed. A random sampling (Monte Carlo) technique is then used to develop the desired number of wind speed records corresponding to a desired number of randomly spaced sites. These simulated wind speed records may be used as the required input to estimate the power that specific single or multiple wind turbines would produce at each site. Summing the power from each of these sites would give a temporal sequential record of the hourly power output from the wind turbine network.

REPRESENTATIVE SITE STATISTICS

The principal input for the model is a real time sequence of hourly wind speeds from a representative site. A site is considered representative if it has the same annual mean wind speed as other typical sites within the region it represents. The model will develop simulated wind speed histories corresponding to sites randomly spaced throughout the region. Thus, the simulated wind histories will, statistically in the limit, have the same mean as the representative site.

The use of a real time sequence as the input to the model provides several important features, including a logical sequence of hourly wind speeds, which is made up of a realistic set of wind speeds, and has a realistic time correlation, diurnal variation, seasonal variation, and probability distribution. If it is desired to simulate details of seasonal and diurnal variations for the regional array, one should select a representative site which has seasonal and diurnal variations of mean wind speed similar to the regional average conditions. The wind speed at the representative site should be taken at, or modified to be equivalent to the wind speed at, a height

equal to the hub height of the wind turbines to be used. This modification could be made after the simulation if wind turbines of various hub heights were used. The model will be estimating wind speeds at the same height as they are taken at the representative site; therefore, if another height is desired, the wind speeds must be modified by an appropriate power or log law.

The statistic (other than the mean wind speed) that is needed at the representative site is the probability distribution, $H(V_s)$, of wind speed, V . That is,

$$H(V_s) = \int_0^V p(V) dV ,$$

where $p(V)$ is the probability density distribution (frequency distribution) of wind speed. If $H(V_s)$ is not known, the following substitution may be made:

$$H(V_s) = 1 - \exp \left[-\frac{\pi}{4} \left(\frac{V_s}{\bar{V}_s} \right)^2 \right] . \quad (1)$$

This equation is a special case of the general form

$$H(V_s) = 1 - \exp \left[-\left(\Gamma \left(\frac{1}{K_s} + 1 \right) \frac{V_s}{\bar{V}_s} \right)^{K_s} \right] \quad (2)$$

when $K_s = 2$, where

V_s = hourly wind speed at representative site

$\bar{V}_s$ = annual mean wind speed at representative site

Γ = gamma function

K_s = Weibull shape parameter for representative site,

Equation 1 corresponds to a $p(V)$ of:

$$p(v_s) = \frac{\pi}{2} \frac{v_s}{\bar{v}_s^2} \exp \left[-\frac{\pi}{4} \left(\frac{v_s}{\bar{v}_s} \right)^2 \right] , \quad (3)$$

which is known as the Rayleigh distribution and has been shown by Cliff⁽³⁾ and Wentink⁽⁴⁾ to give reasonable estimates of power output from wind turbines when only the annual mean wind speed at the 10 meter level is known and is greater than about 4 m/s (9 mph) at the 10 meter level. Justus⁽⁵⁾ has shown that average output power is not sensitive to the shape of the wind distribution (K_s value) if the rated speed V_r , relative to the average speed $\bar{v}_s$ is in the range $0.6 \leq \bar{v}_s/V_r \leq 0.7$ and K_s can be conveniently taken as 2.0. Justus⁽⁶⁾ gives values of K_s (obtained from measurements around the United States) for various mean wind speeds which may yield better estimates of K_s for specific locations of wind speeds; however, Corotis⁽⁷⁾ notes that with the kind of year-to-year variation expected during the operation of a wind energy conversion system, there seems to be no need to provide a model with more accuracy than the Rayleigh distribution, $K_s = 2.0$. If the annual mean wind speed is less than 4.5 m/s at hub height, Justus' report⁽⁴⁾ may be used to derive an estimate of $H(V_s)$ for the site, and the economics of using wind power for the area should perhaps be questioned.

REGIONAL AVERAGE STATISTICS

Justus⁽²⁾ has shown empirically that a reasonable fit for the probability distribution of regional hourly average wind speed, $H(V_A)$, is given by

$$H(V_A) = 1 - \exp \left[- \left(\frac{\Gamma \left(\frac{1}{K_A} + 1 \right) V_A}{\bar{V}_A} \right)^{K_A} \right] , \quad (4)$$

where

V_A = regional hourly wind speed

$\bar{V}_A = \bar{V}_S$ = regional annual mean wind speed

K_A = constant depending on regional size and K_S

Γ = gamma function.

(NOTE: We have previously stated that $\bar{V}_S$ for the representative site is equal to $\bar{V}_A$.)

Justus⁽²⁾ gives K_A as a function of the average correlation between sites within the region, the Weibull shape parameter for the representative site (K_S), and the number of sites. This function of K_A (for a large number of sites) becomes:

$$\frac{K_A}{K_S} = \rho^{-0.543} . \quad (5)$$

Here, ρ is the average correlation between sites and is defined as

$$\rho = \exp \left[- \left(\frac{\bar{r}}{520} \right)^{0.57} \right] , \quad (6)$$

where $\bar{r}$ is in km and is equal to the average distance between sites.

For a circle of diameter D (radius R), $\bar{r}$ calculated about the center of the circle is equal to

$$\bar{r} = \int_0^R rp(r)dr = \frac{2R}{3} = \frac{D}{3}^* , \quad (7)$$

where

$$p(r) = \frac{2r}{R^2} .$$

Thus, for a circle, Equation (6) becomes

$$\rho = \exp \left[- \left(\frac{D}{1560} \right)^{0.57} \right] . \quad (8)$$

Equations (4) through (8) define the probability distribution of the hourly wind speed averaged over the region. Note that for regions less than 2000 km in diameter, $\Gamma(1/K_A + 1)$ (from Equation (5)) has a value within 3% of $(\pi/4)^{1/2}$. Therefore, it is recommended that this approximation be used since the use of a model of this nature would have questionable value for regions on the order 2000 km or greater.

*Justus and Mikhail⁽²⁾ calculated $\bar{r}$ for a large number of sites randomly spaced within a near circular region and found $\bar{r} \simeq D/2.64$. Thus for a noncentral representative site one could use

$$\bar{r} = \frac{D}{2.64} \text{ and } \rho = \exp \left[- \left(\frac{D}{1373} \right)^{0.57} \right] .$$

The next wind statistic required for the model is the probability distribution of hourly wind speed throughout the region, $H(V_{ts})$, given a mean wind speed averaged over the equivalent sites within the region. This probability distribution has two boundary conditions. First, when the size of the region in question shrinks to a point (single site), the density distribution, $P(V_{ts})$, must become a Dirac delta function at the regional average hourly wind speed. Second, equating time and space statistics and letting the regional size approach global extent, the distribution must approach the distribution given by Equation (1). Using the correlation parameter, ρ , defined in Equation (8), the required form of the equation for the probability distribution of wind speed, $H(V_{ts})$ in the region is expressed as:

$$H(V_{ts}) = 1 - \exp \left[- \left(\frac{\Gamma \left(\frac{(1 - \rho)^c}{K_s} + 1 \right) V_{ts}}{V_A} \right)^{K_s / (1 - \rho)^c} \right] \quad (9)$$

where c is an empirical constant estimated to be equal to 0.5 based upon unpublished results of Justus' array work.* Thus $H(V_{ts})$, for the present time, will be computed by the following.

$$H(V_{ts}) = 1 - \exp \left[- \left(\frac{\Gamma \left(\frac{(1 - \rho)^{0.5}}{K_s} + 1 \right) V_{ts}}{V_A} \right)^{K_s / (1 - \rho)^{0.5}} \right] \quad (10)$$

*These results will appear in the next Annual Report to the DOE from the Georgia Institute of Technology by C. G. Justus.

SELECTION OF VELOCITY AT RANDOM SITES

The frequency distribution for hourly wind speeds in a region has been given by Equations (9) and (10). However, the distribution is a function of the hourly wind speed averaged over the region. The technique employed to obtain the hourly regional average wind speed is to take the hourly wind speed from the representative site and equate the value of the representative site's probability distribution at this value of wind speed to the probability distribution of the region, and solve for the appropriate hourly regional average wind speed.

If one uses Equation (1) as an approximation to the probability distribution for a single site (i.e., $K_S = 2$), the probability matching yields*

$$V_A = \frac{\bar{V}_S}{\Gamma\left(\frac{1}{K_A} + 1\right)} \left[\frac{\pi}{4} \left(\frac{V_S}{\bar{V}_S} \right)^2 \right]^{1/K_A} \quad (11)$$

which, when the region is less than 2000 km in diameter, may be approximated by

$$V_A \simeq C_1 V_S^{2/K_A} \quad (12)$$

where

$$C_1 = \left[\left(\frac{4}{\pi} \right)^{1/2} \bar{V}_S \right]^{\frac{K_A - 2}{K_A}} \quad (13)$$

*For the case when $K_S \neq 2$, Equation (2) and (4) should be set equal and V_A solved for. Equation B16 of Ref. 1 also gives this result.

From Equation (5),

$$K_A = 2\rho^{-0.543}$$

and from Equation (8),

$$\rho = \exp\left[-\left(\frac{D}{1560}\right)^{0.57}\right]$$

where D (km) is the diameter of the region in question.

Example Case 1

Diameter of region = 500 km

$$\bar{V}_S = \bar{V}_A = 10 \text{ m/s}$$

$$V_S = 5 \text{ m/s}$$

Equation (11) gives $V_A = 6.09 \text{ m/s}$

Equation (12), which is an approximation to Equation (11), gives

$$V_A = 6.11 \text{ m/s.}$$

The differences in the values generated by Equations (11) and (12) are well within the accuracy of the presented model. It is therefore recommended that Equation (12) be used if the regional diameter is less than 2000 km.

Figure 1 graphically depicts the probability matching process for this example.

With the values of V_A and ρ solved, Equation (10) is completely defined. The following technique will be used to establish the wind speed at each of N sites. First, Equation (10) is rewritten as:

FIGURE 1. Method of Probability Matching to Determine V_A
 (The Average Wind Speed Over an Area)
 (--- Indicates frequency matching for Example 1)

$$V_{ts} = \frac{V_A \left[-\ln(1 - H(V_{ts})) \right]^{\frac{(1-\rho)^{0.5}}{2}}}{\Gamma \left[\frac{(1-\rho)^{0.5}}{2} + 1 \right]} \quad (14)$$

Next, a random number generator (or table of random numbers) is used to produce N random numbers with values between 0.0 and 1.0, each representing sites 1 to N. These numbers are then used as values of $H(V_{ts})$ and the corresponding values of V_{ts} are solved for. Thus the first random number is used for $H(V_{ts})$ in Equation (14), resulting in the velocity, V_{ts} , for the first site; the second random number is used for $H(V_{ts})$ in Equation (14), resulting in the velocity at the second site, and so on, until the N desired has a velocity, V_{ts} , corresponding to the hourly wind speed at the Nth site. Table 1 is an example of 14 wind speeds selected for Example Case 1 using a random number table. Figure 2 graphically depicts the technique used to find the velocity at the random sites. The first four random numbers from Table 1 were used in Figure 2 to graphically show the process of relating the random numbers used as $H(V_{ts})$ values to corresponding values of velocity.

TABLE 1. Example of Velocity Selection for Random Sites
(Random numbers taken from
a table of random numbers)

<u>Site No.</u>	<u>Random Number^(a) = H(V_{ts})</u>	<u>V_{ts} (m/s)</u> <u>(D = 500 km)</u>
1	0.133	3.67
2	0.168	3.98
3	0.741	7.52
4	0.920	9.18
5	0.247	4.57
6	0.367	5.32
7	0.008	1.47
8	0.229	4.45
9	0.022	2.02
10	0.516	6.16
11	0.073	3.00
12	0.765	7.69
13	0.973	10.29
14	0.460	<u>5.85</u>

Mean = 5.36 m/s

(NOTE: These average values would equal 6.11 m/s if a very large number of random numbers were used. Each new set of random numbers would produce a different mean value for the random sites; this is required because the processes involved are stochastic. Note that a larger correlation value (smaller D) will always force V_{ts} toward the mean value of the area. If $\rho = 1$, all V_{ts} would equal the area average.

^(a) New random numbers must be selected for each hourly computation.

FIGURE 2. Probability Distribution of Wind Speed in Region for Example 1

SIMULATION OF THE TEMPORAL SEQUENCE OF HOURLY WIND SPEEDS AT RANDOM SITES

The values of the next hourly wind speed at each of the sites are determined by taking the value of the next hourly wind speed from the representative site, solving for V_A using Equation (12), selecting N new random numbers, and solving for the hourly wind speed at each site V_{ts} using Equation (14). This process is repeated until the desired length of record for the random sites has been established.

To simulate the time sequence of power produced by wind turbines at the sites, one assumes that a desired size and number of machines is located at the N random sites. Use of the wind turbine characteristics, together with the time sequence of the simulated wind speeds at each site, yields a time sequence of wind turbine power produced at each site. The summation of these wind turbine powers from the N sites results in a time sequence of power output from the wind turbines.

This modeling technique relies on the fact that a uniform probability density distribution of $H(V)$ results in a probability density distribution of wind speed, $p(V)$, equal to $dH(V)/dV$. This equality is desired so that the simulated wind records will have the proper statistical properties. This effect is graphically illustrated in Figure 3, where $H(V)$ was sampled at 0.05 intervals and the corresponding velocities were graphically located.

FIGURE 3. Uniform Spacing of $H(V)$ and Resultant Spacing of Velocity

CONCLUSIONS

This report develops a model by which simulations of hourly wind speeds may be generated for any desired number of random sites with a region of a given size. Using these wind histories in conjunction with the operating characteristics of wind turbines, simulations of power output time histories from wind turbine arrays may be generated.

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APPENDIX A

STEP-BY-STEP PROCEDURE TO PERFORM SEQUENTIAL
SIMULATION OF HOURLY WIND SPEEDS AT RANDOM SITES

APPENDIX A

STEP-BY-STEP PROCEDURE TO PERFORM SEQUENTIAL SIMULATION OF HOURLY WIND SPEEDS AT RANDOM SITES

1. From a representative site^(a) obtain the probability distribution, $H(V_s)$, for wind speed or use

$$H(V_s) = 1 - \exp \left[-\frac{\pi}{4} \left(\frac{V_s}{\bar{V}_s} \right)^2 \right] \quad (A-1)$$

as an approximation, where V_s is wind speed and $\bar{V}_s$ is the annual average wind speed.

2. Calculate the quantity K_A :

$$K_A = 2\rho^{-0.543} \quad (A-2)$$

where

$$\rho = \exp \left[-\left(\frac{D}{1560} \right)^{0.57} \right] \quad (A-3)$$

and D is the diameter of the region being considered.

3. Using a time sequence of hourly values of wind speed, V_s , from the representative site, compute a time sequence of regional hourly wind speeds, V_A , from the following:

$$V_A = C_1 V_s^{2/K_A} \quad (A-4)$$

(a) A site is considered representative if its annual mean wind wind speed is representative of the annual mean wind speed at other typical sites within the region. This simulation scheme develops wind histories at random locations, but the expected annual mean at each site is the same.

where

$$C_1 = \left[\left(\frac{4}{\pi} \right)^{\frac{1}{2}} \bar{V}_s \right]^{\frac{K_A - 2}{K_A}} \quad (A-5)$$

4. For each hour, select N random numbers, $H(V_{ts})$, between 0 and 1, where N equals the number of sites desired (i.e., for each hour let the first random number represent the first site, the second random number represent the second site, etc.).
5. For each random number, $H(V_{ts})$, calculate a corresponding velocity, V_{ts} .

$$V_{ts} = \frac{V_A \left[-\ln(1 - H(V_{ts})) \right]^{\frac{(1-\rho)^{0.5}}{2}}}{\Gamma \left[\frac{(1-\rho)^{0.5}}{2} + 1 \right]} \quad (A-6)$$

6. The values calculated in step 5 now give N simulated wind speed records for the N desired sites. These wind speed records may be used in conjunction with desired wind turbine operating characteristics to produce time histories of the wind power developed at each site. The sum of the power generated each hour at all sites then simulates a time history of the total power produced by the wind turbines located at the sites. The postulated wind turbines may be single or multiple units at each site.

APPENDIX B

A COMPUTER PROGRAM TO COMPUTE THE SIMULATED
HOURLY WIND SPEEDS AT N RANDOMLY DISPERSED SITES

APPENDIX B

A COMPUTER PROGRAM TO COMPUTE THE SIMULATED HOURLY WIND SPEEDS FOR RANDOMLY DISPERSED SITES

This appendix presents a computer program in the form of a subroutine which will compute simulated hourly wind speeds for any desired number, N , of hypothetical sites randomly dispersed throughout a region of specified size. The subroutine is designed to be used with any program which will provide it with a wind speed from a single anemometer within the region. The small driving program, shown with the subroutine on Table B-1, was assembled to test the subroutine. An example case is presented to show the effect of region size on the simulated wind speed sequences. Tables B-2, B-3 and B-4 each present 10 wind speed simulations for regions with diameters 500 km, 50 km and 5 km, respectively. The same set of random numbers, Table B-5, were used in each case for the computation of the simulated wind speeds. It is seen from Tables B-2, B-3 and B-4 that the smaller the region size, the closer the simulated wind speeds approach the representative site's wind speed.

Inputs to the driving program for the test case are:

<u>Card 1</u>	D	=	diameter of region in km
	VBARS	=	annual mean wind speed at representative site
	NS	=	number of sites
	NHRS	=	number of consecutive hours to be simulated
<u>Cards 2</u>	V_s	=	consecutive values of the hourly wind speed at the representative site to be used as input for the simulation scheme

The probability distribution for the representative site as defined by Equation (A-1) is used in subroutine NSITES.

TABLE B-1. Computer Program to Compute the Simulated Hourly Wind Speeds at N Randomly Dispersed Sites

```

PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
  DIMENSION VS(25),VTS(10)
  READ 10,D,VBARS,NS,NHRS
10  FORMAT(2F10.0,2I5)
  READ 11,VS
11  FORMAT(16F5.0)
  PRINT 1
  1  FORMAT(1H1)
C*****PRINT TITLING HERE
  PRINT 20,VBARS,D,NS
20  FORMAT(1H0,44X,"SIMULATION OF WIND SPEEDS AT RANDOM SITES"//
+57X,"EXAMPLE COMPUTATION"//25X,"VBARS=",F6.2,"M/S",5X,"D=",F6.1,
+"KM",5X,"NUMBER OF SITES=",I3)
  PRINT 21
21  FORMAT(1H0,T62,"WIND SPEEDS",T101,"MEAN OF",T112,"AREA"/T19,10I4X,
+"SITE",I,X,"SIMULATED",T112,"MEAN")
  PRINT 22
22  FORMAT(1H ,T6,"HOUR",T13,"REP SITE",T25,"1",T33,"2",T41,"3",T49,"4
+",T57,"5",T65,"6",T73,"7",T81,"8",T89,"9",T96,"10",T103,"SITES",
+T111,"SPEED")
  DO 50 J=1,NHRS
    ANV=VS(J)
    CALL NSITES(D,VBARS,NS,ANV,AVTS,VA,VTS)
    IHR=J-1
    PRINT 200,IHR,VS(J),VTS,AVTS,VA
200  FORMAT(1H0,I7,F11.2,12F6.2)
  50  CONTINUE
  STOP
  END

SUBROUTINE NSITES(D,VBARS,NS,ANV,AVTS,VA,VTS)
C*****D- DIAMETER OF THE AREA (KM) (FROM MAIN)
C*****VBARS- MEAN ANNUAL WIND SPEED AT THE REPRESENTATIVE SITE (M/S) (FROM MAIN)
C*****NS- NUMBER OF SITES FOR WHICH RANDOM WINDSPEEDS ARE TO BE GENERATED
C***** (FROM MAIN)
C*****ANV- A SINGLE HOURLY WIND SPEED AT THE REPRESENTATIVE SITE (M/S)
C***** (FROM MAIN)
C*****AVTS- VARIABLE USED TO SUM NS SITE WIND SPEEDS. FINALLY AVTS IS SET = TO
C*****THE HOURLY ARITHMETIC MEAN OF THE WIND SPEEDS GENERATED AT NS RANDOM
C*****SITES (COMPUTED IN NSITES)
C*****VA- MEAN WIND SPEED OF THE ENTIRE AREA (M/S) (COMPUTED IN NSITES)
C*****VTS- ARRAY CONTAINING HOURLY WIND SPEED (M/S) FOR EACH OF THE RANDOM SITES
C***** (COMPUTED IN NSITES)
  DIMENSION GAM(51),VTS(1)
  DATA GAM/1.00,.994,.989,.984,.978,.974,.969,.964,.960,.955,.951,
+.947,.944,.940,.936,.933,.930,.927,.924,.921,.918,.916,.913,.911,
+.909,.906,.904,.902,.901,.899,.897,.896,.895,.893,.892,.891,.890,
+.889,.888,.888,.887,.887,.886,.886,.886,.886,.886,.886,.886,
+.886/
  DATA PI/3.1416/
  DATA KMOD/0/
  IF(KMOD.GE.1) GO TO 15
  RHO=EXP(-(D/1560.)**.57)
  ERHO=SQRT(1.-RHO)/2.
  RKA=2.*(RHO**(-.543))
  C1=(SQRT(4./PI)*VBARS)**((RKA-2.)/RKA)
  KRHO=(ERHO+1.)*100.-99.
  GRHO=GAM(KRHO)
  KMOD=1
15  CONTINUE
  VA=C1*ANV**(2./RKA)
  AVTS=0.
  DO 25 I=1,NS
    HVTS=KANF(A)
    VTS(I)=(VA/GRHO)*(-ALOG(1.-HVTS))**ERHO
    AVTS=AVTS+VTS(I)
25  CONTINUE
  AVTS=AVTS/FLOAT(NS)
  RETURN
  END

```


SIMULATION OF WIND SPEEDS AT RANDOM SITES

EXAMPLE COMPUTATION

VBARS= 10.00M/S

D= 500.0KM

NUMBER OF SITES= 10

HOUR	REP SITE	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	WIND SPEEDS		SITE 8	SITE 9	SITE 10	MEAN OF SIMULATED SITES	AREA MEAN SPEED
0	10.00	10.99	16.34	13.21	8.25	9.79	2.28	8.01	9.34	12.09	9.11	9.84	10.30
1	11.04	6.65	14.90	11.87	6.01	8.64	12.26	5.69	20.22	19.09	13.07	11.84	11.10
2	12.00	18.16	8.35	7.04	16.42	15.65	12.18	3.72	9.66	14.85	18.40	12.44	11.82
3	12.83	9.85	13.31	18.18	17.78	12.30	11.15	17.45	18.99	13.44	8.74	14.12	12.43
4	13.46	18.47	12.37	14.33	12.17	12.30	9.45	16.16	13.88	12.13	12.74	13.40	12.89
5	13.86	19.82	9.27	17.68	8.29	17.98	15.30	19.96	11.39	9.92	10.32	13.99	13.17
6	14.00	11.68	7.06	10.83	15.26	15.05	13.30	8.91	11.79	7.60	18.21	11.97	13.27
7	13.86	15.74	15.91	14.82	3.93	6.41	21.04	12.15	11.71	14.35	19.11	13.52	13.17
8	13.46	6.41	13.70	18.98	13.65	7.50	16.49	13.85	10.07	12.24	9.42	12.23	12.89
9	12.83	13.77	16.22	7.54	12.53	13.89	15.26	14.74	12.42	15.37	13.05	13.48	12.43
10	12.00	9.59	11.58	16.68	15.36	4.85	17.15	16.26	16.26	13.86	11.75	13.33	11.82
11	11.04	7.69	7.46	8.89	15.34	6.45	7.93	14.61	17.74	11.38	11.81	10.93	11.10
12	10.00	12.53	8.91	11.62	10.29	14.75	9.13	12.93	14.63	6.12	5.09	10.60	10.30
13	8.96	11.91	14.15	11.91	9.48	9.61	15.11	15.27	14.19	11.76	7.83	12.12	9.49
14	8.00	11.36	12.89	11.75	7.43	11.32	8.32	8.99	12.17	7.37	6.94	9.85	8.71
15	7.17	9.50	7.42	5.44	3.81	4.14	9.84	8.18	7.90	4.45	7.01	6.37	8.02
16	6.54	2.92	5.04	11.22	8.82	8.29	11.75	12.01	6.10	7.59	6.29	8.20	7.48
17	6.14	5.25	7.67	7.93	6.52	6.73	8.24	4.85	7.77	7.23	7.78	7.80	7.14
18	6.00	5.41	9.60	4.36	7.00	5.67	6.17	4.68	5.36	9.26	5.64	6.32	7.01
19	6.14	12.38	1.26	5.68	3.13	5.09	7.25	3.95	7.33	7.68	8.82	6.25	7.14
20	6.54	3.14	3.55	3.71	6.81	7.03	9.68	6.77	9.35	6.83	7.01	6.39	7.48
21	7.17	4.64	8.38	8.80	9.12	9.73	5.56	12.40	6.84	4.22	14.84	8.45	8.02
22	8.00	6.81	8.23	10.13	5.88	5.50	11.26	13.94	5.09	8.02	2.96	7.78	8.71
23	8.96	11.01	3.63	7.34	10.13	6.12	10.28	6.63	12.43	7.99	8.07	8.37	9.49
24	10.00	4.94	4.74	7.19	6.25	13.65	7.80	8.45	7.81	4.56	4.75	7.81	10.30

TABLE B-2. Example Computation of 25 Hours of Input from a Representative Site: Region Diameter = 500 km. (For this example the wind velocity at the representative site was defined by $V_s = 10 + 4 \sin \pi t/12$ where t represented hours.)

SIMULATION OF WIND SPEEDS AT RANDOM SITES

EXAMPLE COMPUTATION

VHARS = 10.00M/S

D = 50.0KM

NUMBER OF SITES = 10

HOOR	REF SITE	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	WIND SPEEDS SITE 6	SITE 7	SITE 8	SITE 9	SITE 10	MEAN OF SIMULATED SITES	AREA MEAN SPEED
0	10.00	10.64	13.33	11.81	9.04	9.97	4.36	8.90	9.10	11.23	9.57	9.79	10.09
1	11.04	8.41	13.22	11.64	7.94	9.76	11.90	7.69	15.81	15.30	12.34	11.41	11.06
2	12.00	15.50	9.97	9.05	14.64	14.25	12.35	6.30	10.83	13.43	15.62	12.24	11.95
3	12.83	11.32	13.44	16.04	15.84	12.85	12.15	15.67	16.44	13.51	10.58	13.78	12.71
4	13.46	16.57	13.20	14.35	13.08	13.16	11.33	15.37	14.09	13.05	13.47	13.76	13.29
5	13.86	17.50	11.37	16.41	10.67	16.55	15.11	17.57	12.78	11.82	12.09	14.19	13.65
6	14.00	13.03	9.79	12.49	15.16	15.05	14.03	11.17	13.10	10.21	16.77	13.08	13.78
7	13.86	15.36	15.45	14.84	6.94	9.22	18.11	13.26	12.95	14.57	17.14	13.79	13.65
8	13.46	9.09	13.99	16.83	13.96	9.93	15.54	14.08	11.74	13.12	11.31	12.96	13.29
9	12.83	13.70	15.03	9.73	12.98	13.76	14.52	14.24	12.92	14.59	13.29	13.47	12.71
10	12.00	10.79	12.01	14.77	14.10	7.33	15.01	14.56	14.66	13.29	12.11	12.85	11.95
11	11.04	9.13	8.97	9.91	13.51	8.26	9.29	13.14	14.66	11.41	11.65	10.99	11.06
12	10.00	11.47	9.45	10.98	10.25	12.58	9.58	11.67	12.52	7.63	6.87	10.30	10.09
13	8.96	10.55	11.63	10.55	9.26	9.13	12.07	12.14	11.65	10.47	8.31	10.60	9.11
14	8.00	9.70	10.42	9.89	7.62	9.68	8.13	8.49	10.09	7.59	7.34	8.90	8.20
15	7.17	8.30	4.65	6.05	4.94	5.18	8.47	7.62	7.45	5.40	6.99	6.51	7.41
16	6.54	4.06	5.53	8.71	7.60	7.33	8.94	9.05	7.24	6.93	6.27	7.17	6.81
17	6.14	5.49	6.80	6.93	6.20	6.31	7.08	5.25	6.85	6.58	6.86	6.44	6.42
18	6.00	5.52	7.64	4.88	6.38	5.67	5.95	5.08	5.49	7.48	5.65	5.97	6.29
19	6.14	8.92	2.43	5.73	4.09	5.19	6.59	4.66	6.63	6.81	7.36	5.86	6.42
20	6.54	4.23	4.54	4.65	6.56	6.68	8.01	6.54	7.85	6.57	6.67	6.23	6.81
21	7.17	5.53	7.73	7.94	8.11	8.41	6.12	9.65	6.89	5.23	10.69	7.63	7.41
22	9.00	7.25	8.08	9.09	6.68	6.43	9.65	10.90	6.15	7.96	4.52	7.67	8.20
23	8.96	10.09	5.37	8.02	9.62	7.23	9.70	7.56	10.80	8.41	8.46	8.53	9.11
24	10.00	6.76	6.60	8.36	7.72	12.03	8.76	9.16	8.77	6.46	6.61	8.12	10.09

TABLE B-3. Example Computation of 25 Hours of Input from a Representative Site: Region Diameter = 50 km. (For this example the wind velocity at the representative site was defined by $V_S = 10 + 4 \sin \pi t/12$ where t represented hours.)

SIMULATION OF WIND SPEEDS AT RANDOM SITES

EXAMPLE COMPUTATION

VHARS= 10.004/5

D= 5.0KM

NUMBER OF SITES= 10

HOUR	REF SITE	WIND SPEEDS										MEAN OF SITE SIMULATED SITES	AREA MEAN SPEED
		SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8	SITE 9	SITE 10		
1	10.00	10.35	11.67	10.95	9.50	10.00	8.44	9.41	9.52	10.66	9.78	9.83	10.02
2	11.04	9.59	12.23	11.42	9.30	11.37	11.53	9.14	13.41	13.18	11.75	11.19	11.04
3	12.00	13.62	10.93	10.38	13.41	13.21	12.25	9.56	11.42	13.01	13.08	12.09	11.98
4	12.43	12.08	13.23	14.54	14.44	12.92	12.55	14.36	14.73	13.27	11.65	13.38	12.80
5	13.46	15.15	13.42	14.03	13.35	13.39	12.37	14.55	13.89	13.34	13.54	13.70	13.41
6	13.86	15.82	12.57	15.29	12.15	15.35	14.63	15.85	13.38	12.83	12.99	14.09	13.80
7	14.00	13.59	11.67	13.28	14.73	14.57	14.13	12.52	13.62	11.93	15.53	13.57	13.94
8	13.86	14.75	14.80	14.49	9.70	11.25	16.11	13.64	13.49	14.35	15.64	13.82	13.80
9	13.46	11.00	13.84	15.27	13.82	11.53	14.64	13.99	12.61	13.37	12.36	13.23	13.41
10	12.83	13.37	14.05	11.14	12.99	13.40	13.79	13.65	12.96	13.82	13.15	13.23	12.80
11	12.00	11.40	12.06	13.47	13.14	9.28	13.59	13.37	13.37	12.74	12.12	12.45	11.98
12	11.04	10.01	9.92	10.46	12.34	9.50	10.11	12.16	12.89	11.27	11.40	11.01	11.04
13	10.00	10.77	9.72	10.53	10.15	11.32	9.79	10.88	11.29	8.67	8.21	10.13	10.02
14	8.96	9.77	10.29	9.77	9.12	9.15	10.50	10.53	10.30	9.73	8.60	9.78	9.00
15	8.00	8.84	9.19	8.93	7.78	8.83	8.05	8.24	9.03	7.76	7.62	8.43	8.06
16	7.17	7.71	5.67	6.52	5.86	6.00	7.80	7.37	7.30	6.14	7.04	6.74	7.24
17	6.54	5.04	5.94	7.57	7.04	6.91	7.68	7.73	6.86	6.73	6.36	6.79	6.61
18	6.14	5.74	6.44	6.50	6.13	6.19	6.58	5.60	6.46	6.32	6.46	6.24	6.22
19	6.00	5.69	6.77	5.33	6.15	5.77	5.92	5.45	5.68	6.70	5.77	5.92	6.08
20	6.14	7.44	7.72	5.88	4.91	5.69	6.33	5.26	6.35	6.44	6.71	5.87	6.22
21	6.54	5.15	5.35	5.42	6.51	6.57	7.24	6.50	7.16	6.52	6.57	6.30	6.61
22	7.17	6.21	7.43	7.54	7.62	7.77	6.56	8.36	6.99	6.04	8.83	7.33	7.24
23	8.00	7.57	8.02	8.54	7.25	7.10	8.82	9.41	6.94	7.96	5.89	7.75	8.06
24	8.96	9.54	6.82	8.45	9.30	7.99	9.34	8.18	9.90	8.66	8.69	8.69	9.00
25	10.00	8.13	8.03	9.11	8.73	11.05	9.34	9.56	9.34	7.94	8.03	8.93	10.02

TABLE B-4. Example Computation of 25 Hours of Input from a Representative Site: Region Diameter = 5 km. (For this example the wind velocity at the representative site was defined by $V_s = 10 + 4 \sin \pi t/12$ where t represented hours.)

TABLE B-5. Random Numbers Used in the Computation
of Tables B-2, B-3, and B-4

.580	.951	.796	.298	.454	.006	.276	.306	.689	.383
.133	.832	.583	.099	.277	.620	.094	.990	.979	.694
.934	.212	.131	.863	.819	.541	.019	.314	.765	.942
.280	.585	.903	.887	.497	.396	.872	.931	.595	.210
.880	.464	.628	.447	.458	.235	.764	.591	.444	.495
.922	.210	.832	.153	.846	.678	.926	.362	.253	.281
.370	.093	.313	.666	.650	.510	.194	.386	.116	.852
.710	.722	.641	.016	.072	.954	.423	.387	.604	.897
.076	.576	.908	.572	.122	.784	.589	.279	.453	.233
.624	.804	.137	.516	.634	.740	.702	.507	.749	.562
.300	.485	.876	.801	.043	.897	.855	.854	.689	.501
.201	.194	.298	.858	.122	.219	.813	.954	.536	.577
.730	.762	.644	.506	.887	.384	.764	.881	.129	.075
.765	.917	.765	.507	.522	.953	.957	.918	.751	.322
.804	.911	.837	.350	.801	.459	.543	.868	.742	.294
.700	.048	.189	.067	.086	.740	.530	.492	.106	.372
.036	.186	.920	.695	.623	.946	.954	.596	.524	.337
.237	.589	.627	.414	.445	.671	.191	.603	.523	.605
.270	.850	.148	.505	.306	.378	.181	.263	.916	.302
.981	.003	.293	.052	.218	.524	.105	.537	.590	.747
.046	.066	.076	.409	.442	.795	.404	.759	.412	.439
.120	.557	.612	.654	.727	.201	.938	.350	.090	.992
.279	.448	.680	.187	.154	.795	.955	.123	.422	.024
.670	.034	.274	.581	.164	.598	.206	.809	.339	.348
.060	.060	.205	.138	.819	.257	.316	.257	.054	.061

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