

A Technical Note on Micro-siting of Wind Turbines

1.0 Introduction

Wind turbines are often deployed in large numbers in a given windy area. They offer a unique opportunity to increase the total installed capacity to the required level in a modular fashion. While doing so, it becomes necessary to arrange the machines in such a manner that at each location, the operation of the machine has the least interference from other machines and by itself will not cause strong interference to other machines in the vicinity. When a turbine is deployed in a given small area, there will be a change in the wind environment in the immediate surroundings. Two major effects are found to occur. The first one is that the wind speeds behind the rotor will show a drop. The other is that the rotor action introduces an extra turbulence in the wind field. Both these effects will result in reduction of wind power produced by the machines in the "wake" of machines in the front.

In a given array, the drop in generation for a particular machine due to other machines interference in the flow field will vary depending upon its location vis a vis other machines and the flow field. It will be reasonable to take park efficiency as one figure providing that all machines are under one ownership. But, if different people or companies' own individual machines, the net generation a given machine eventually gives has the potential to become a contentious issue. Therefore, it may be essential to keep the array losses in a given wind farming area minimum. In complex terrain, this factor becomes even more critical as the land availability becomes a major limitation.

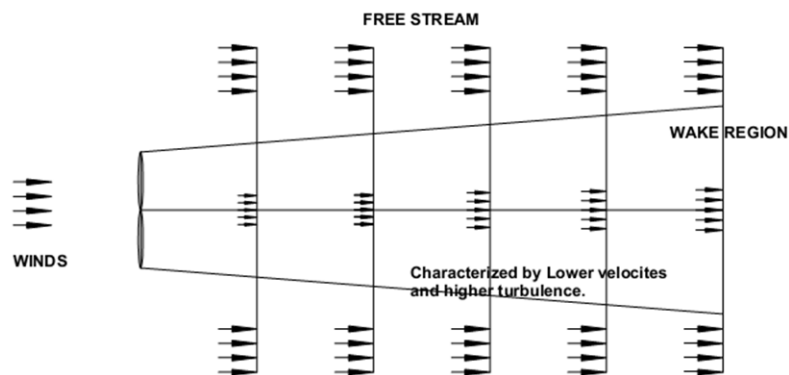


Figure 1. Wake behind a wind turbine rotor

Increased turbulence will also modify the fatigue spectrum that the wind turbine will be subjected to. This effect will be particularly serious on the rotor blades. This factor should also be taken into account while carrying out micro-siting exercises. The point to note is that no immediate effects would be observed in terms of energy generation except that there will be slight drop in generation due to increased turbulence. Increased turbulence has an effect on the service life of a given turbine. The fatigue life of critical components such as blades is determined by the cumulative damage that occurs on the various components due to stress cycling. The fatigue damage due to this effect should be properly estimated and taken into account.

The other aspect is to consider the optimization of land use. Analyses have shown that array losses are higher with close packed wind farms particularly in low to moderate wind regimes.

The science of limiting *array effects* by a suitable geometric arrangement of machine layout is generally known as micro siting of wind turbines. There are no straightforward formulae to do this in practice. The term array efficiency is defined as follows:

$$\text{Array Efficiency} = \frac{E_{\text{park}}}{E_{\text{free}}} * 100$$

Where E_{park} = Output from the machine in the park

E_{free} = Machine output without influence of other machines.

It should be noted that this number would be different for different machines in a given array. The normal practice is to assume an overall percentage for all machines. This is not an acceptable method because it would distort the way results are presented.

The factors affecting the array efficiency are:

1. Mean Wind speeds and pre-dominant wind directions vis a vis available land area.
2. Mean turbulence intensity (TI) and the machine design with regard to TI.
3. Shape, orographic, roughness features and orientation of the land that is made available for wind farming.
4. Number of machines or the Megawatt capacity to be installed.
5. Anticipated park average output in terms of MWH/year

6. Statutory regulations with regard to neighbouring lands.

With these inputs, it will be necessary to carry out an optimization.

2.0 The Procedure:

2.1 Input data to be used:

1. Machine characteristics – Certified Power curve along with the thrust coefficient curve. The manufacturer shall supply the site-specific curves or the curve under standard conditions. If power curve and thrust curves are provided under standard conditions, necessary site corrections shall be incorporated as per standards.
2. The average climatic conditions at the site shall be taken into account. If the site has this information available, it may be used to correct for site's air density and other factors.
3. Validated Orographic and Roughness maps for the region under consideration. The model shall be validated at two or three control points. The land survey with 1 or 2 m contour interval available in electronic form will greatly help in micro siting. The outputs from such a survey may be used to validate the larger orographic model.
4. Wind speed and direction data along with turbulence intensity (TI). If TI information is not available directly, an estimate shall be made. Wind speed information shall be for a full year or multiples of full years. It will never do to use partial year data for this analysis as it will give a very skewed result depending on period of collection. Where feasible, it will be a good idea to use multiple year data rather than just one full year. Wind speed information should be obtained from authenticated sources.

2.2 Calculations:

5. With these inputs, the machine locations shall be fixed in the given area in such a manner that the park average output meets the anticipated levels. There are two opposing needs to be addressed here. On the one hand, the generation levels shall be maximized. On the other, the space occupied by the wind farm be kept to a minimum.
6. Individual machine outputs are estimated using the model and overall outputs are determined for a number of configurations
7. The best wind farm plan shall be adopted for deployment.

It should be noted that a variety of situations will be encountered while planning the layout of wind farms. Normally the layouts are defined in terms of row wise spacing and column wise spacing. Micro-siting of wind turbines has been found to raise many scientific and administrative challenges. The debate as to whether simplified thumb rules can be formulated such that authorities responsible

for granting permissions for wind farming can employ without having to go back to the subject experts cannot be easily settled.

Some broad guidelines can still be formulated to effectively utilize the land and resources. Land in windy areas sells at a premium. In a wind farming project the rough cost break up would be

Cost of WT hardware`	75%
Foundation	07%
Land	02%
Electrical infrastructure	10%
Miscellaneous	06%.

However, if one looks at land utilization point of view, it would become apparent that a given tract of land could accommodate much more installed power both on a per hectare basis and on a yield per hectare basis.

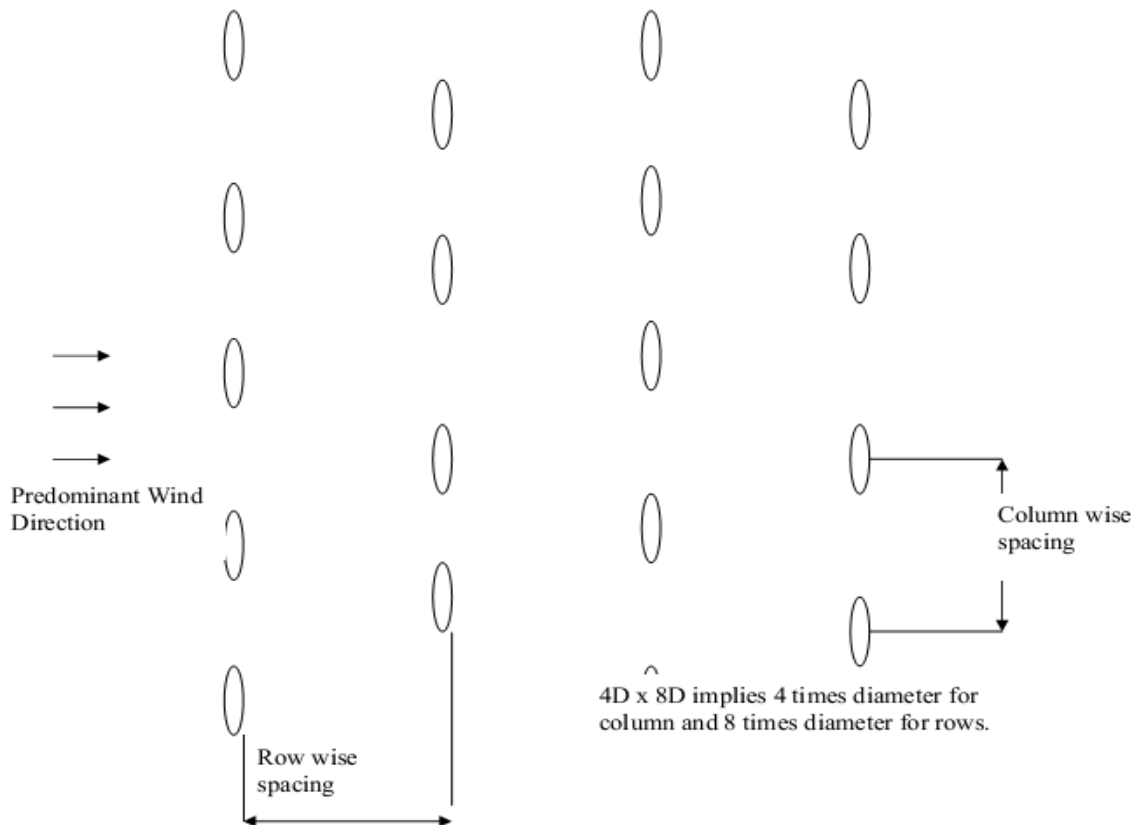


Figure 2. Typical Wind farm array in level terrain

2.3 Level Terrain sites:

These are flat or gently undulating terrain with vast open spaces. It is likely that such areas have agricultural activities including coconut farming and mangroves. An example would be the Udumalpet or Palladam areas in Tamilnadu or plains of Gujarat and Rajasthan. Theoretically, there will be no limit on the area available for wind farming. This will normally depend upon the land ownership related issues. Land use patterns also have a major influence on how much of land will become available for wind farming.

A detailed analysis to determine extent of array losses and related issues has been carried out under identical conditions [2]. The results of this study indicate that:

1. Under high wind conditions, the array spacing can be somewhat tight. That is the machines can be placed close to each other.
2. Under moderate wind conditions, the normally employed 5D X 7D or 4D X 8D may be still acceptable keeping in view multiple ownerships.
3. Taken on a land use efficiency basis, the lost generation due to tighter spacing is somewhat lower than anticipated originally.
4. Inter-column distances should not be less than 3D and inter row less than 5 D.

Most of the level terrain sites are characterized by moderate wind conditions (5.5 to 6.5 m/s annually). There are exceptions to this in some of the recognized localities such as Aralvoimozi pass. But these are not normal circumstances. Such passes need to be considered on a separate footing.

2.4 Complex terrain Sites:

Many complex terrain sites are characterized by high winds and the wind field is also found to be somewhat heterogeneous. That is, the same hill may have wide fluctuations of winds over small areas. Apart from this, the area available for setting up wind machines also will be physically limited. Often it becomes necessary to shift locations due to local defects (sudden depressions, extended cracks on the rocky hill tops etc..) Many of the hilltops would be so narrow that they may have to be flattened to accommodate the machine and the installation equipment. In many cases, it will be feasible to accommodate only one row of machines.

Therefore, much care needs to be taken in case of complex terrain sites while micro siting. Here, each site has to be evaluated on a case-to-case basis. In case of complex terrain sites, it has been found that due to terrain inclination, winds will strike the rotor blades at an angle. This angle should not be more than 5 to 10°. It is important to obtain this information from the machine manufacturer/designer. The manufacturer shall supply information on the maximum angle that is permissible.

In complex terrain, the ambient turbulence intensities are generally high. It is therefore important to keep this in mind while carrying out micro siting. However, the resultant TI will saturate at a value higher than the ambient value, but would not be summed up arithmetically.

3.0 Evaluation tools:

There are a number of tools used for determining the combined effect of deploying wind turbines in arrays. One of the earliest tool is the RISO's PARK program, which was written to be used in conjunction with RISO's WASP. Latest versions of WASP (8.xx) are able to take up the array effect also into account and are found to give reasonable results. In order to determine the turbulence related and terrain induced flow inclinations at each turbine location and its effect, WASP Engineering has been developed and the first version is now available. Windfarmer® from RE-Soft is able to give optimized wind farm configuration in a given area. It also has a facility to incorporate different machines in a given wind farm. Besides these, many other models have been developed over the years.

These methods are essentially based on a simple moment deficit computation scheme. Some studies have indicated that it is feasible to treat windmills as obstacles or roughness elements and carryout the modeling. A number of wind tunnel based studies have yielded some validation of the numerical methods employed. It should, however be cautioned that as with any mathematical modeling, there can be some variations between the calculated and derived values. This remains an area of research.

The alternate method that has not found favor in the industry is the physical model study in a wind tunnel [4]. The results and interpretation of test results have several difficulties including scaling, assignment of roughness turbine model itself. Apart from this, the test section in the tunnel itself would impose various physical limitations on the size of the model. Further, such studies are rather expensive and are found to give results with difficulties of interpretation. Compared to this, the numerical methods are economical and are able to give reasonably good agreement with measurements when employed carefully.

4.0 Micro-Siting Report and Recommendations:

Any application for clearance of setting up a wind farm should be supported by a detailed micro-siting report. The report shall cover:

1. Details of Wind Statistics (joint frequency distribution) at hub height or height of measurement. The furnished details shall include starting and ending dates of data used. It should also be noted that full year statistics alone be used. The source of data shall also be scrutinized for authenticity and integrity.



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2. Estimates of meteorological parameters (site temperature and atmospheric pressure etc.)
3. Detailed description of the wind farm site. If other wind farms or other machines belonging to different clients are in the vicinity, complete details shall be furnished. It will be necessary for the authority giving planning permission to verify this aspect. If very large numbers of machines are in the vicinity, the micro-siting report shall show how the overall effect of presence of these machines is taken into account.
4. Orographic and roughness models used in the analysis shall be furnished. The report shall contain validation of the models employed for arriving at the final generation figures.
5. Complete details of the power curve along with the thrust coefficient shall be given. If a site-specific power curve has been given, the method of transformation from standard power curve shall be specified. If standard power curve has been used, the method of correcting the estimated energy output shall be clearly stated. The class of wind turbine under consideration should be taken into account while deciding the suitability of the specific model. In complex terrain, it becomes very important to cross check each machine location more carefully.
6. Endeavor should be to look at a total area development rather than giving piecemeal approvals. To the extent feasible, a given large area shall be already checked out for array effects and shall be referred to while giving permits for individual projects. This point is borne out by the studies presented in the appendix I. Typical results from detailed calculations indicating the type of array losses encountered in different wind regimes for different array configurations are presented in appendix II.
7. In general, the developer shall leave a distance of $2 \times D$ perpendicular to the predominant wind direction and $3 \times D$ distance in the pre-dominant wind direction. The boundary of the property under consideration as shown in figure 3. This should be applied for flat and complex terrain.
8. The inter-machine spacing within the wind farm shall be decided based on an optimized micro-siting plan agreed to between the developer and end user. However, the inter-machine spacing may be kept at a minimum of $3D$ (perpendicular to wind direction - row) by $5D$ (in the direction of wind - column).
9. In complex terrain, the inter-machine spacing may have to be decided on a case-to-case basis. But in any case the spacing shall not be less than $3D$ in a row perpendicular

to pre-dominant wind direction (row).

10. Estimates of individual machines gross and park outputs shall be given. In no case shall the overall array loss for any individual machine be greater than 15%. The overall wind farm array losses shall not be greater than 10%.
11. Uncertainty calculations on the generation estimates also shall be given. The calculations should include an assessment of measurement site and wind farm site the uncertainty associated with inter-annual variations of average wind environment.

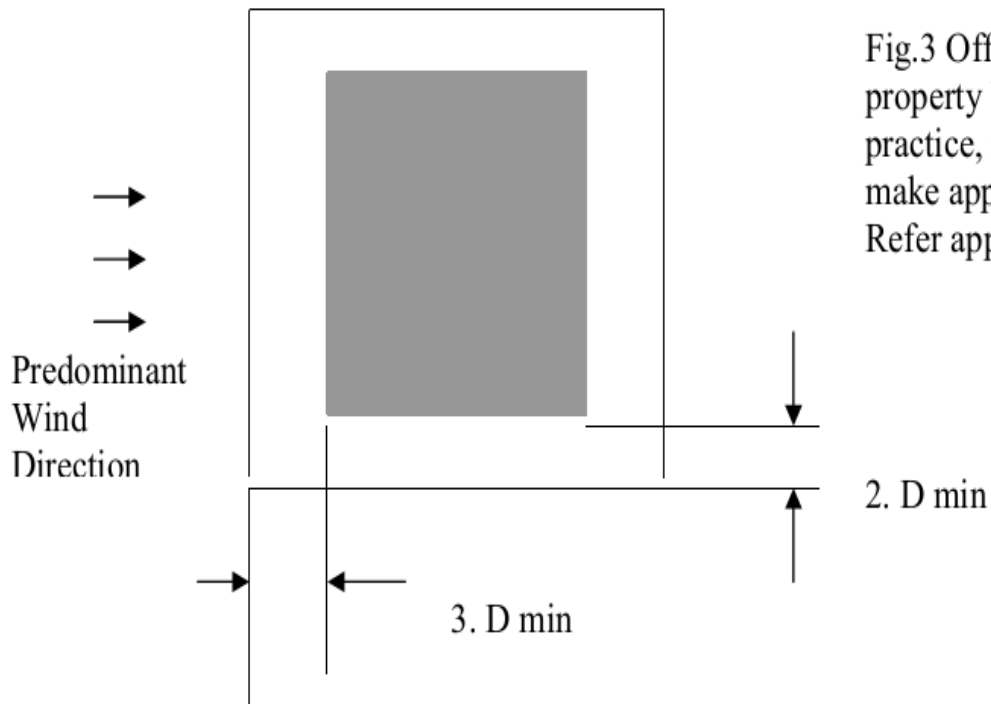


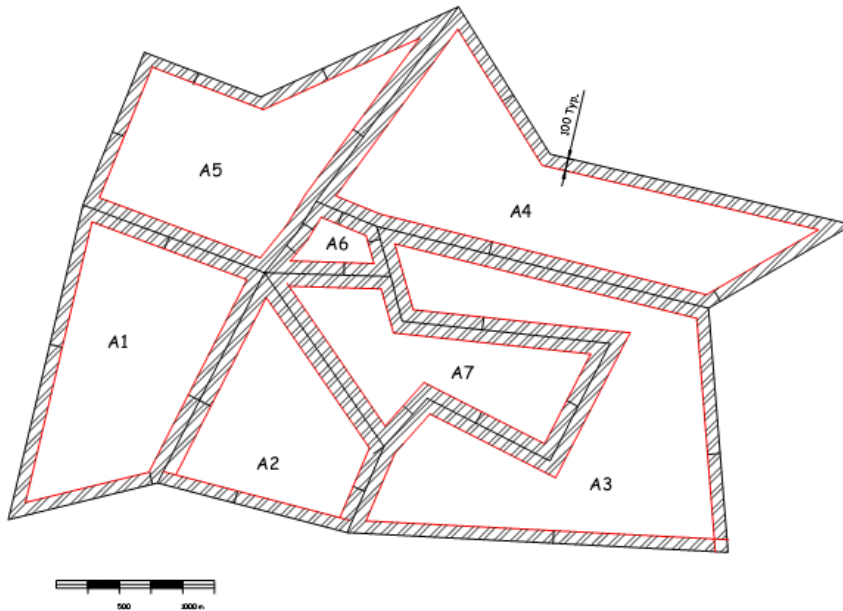
Fig.3 Offsets from property boundary. In practice, it is essential to make approximations. Refer appendix 1

References:

1. Claus Nybroe, Windfarm –Planning Wind Physics, Folkecenter,
2. An exercise in micro-siting, DU/2003/002/p M.P.Ramesh, Executive Director, C-WET
3. Sten Frandsen, RISO - Turbulence and Turbulence generated fatigue loading on wind turbine clusters (personal communication)
4. P.E.J Vermeulen, TNO- Apeldoorn, An experimental analysis of wind turbine wakes. Third International Symposium on Wind Energy Systems.1980.

Appendix I

A typical area that becomes available for wind farming is considered (fig A1). The land consists of a number of land holdings measuring several hectares. There are two ways of looking at such an area. One is to look at the individual land holding and permitting no machines in 100 meters from any boundary line. 100 m offset is chosen keeping in view the machine sizes that are being installed presently. Such an exercise was carried out in an area measuring about 1800 hectares. After the offsets, the remaining area comes down to about 1260 hectares. But within this area if a small holding of say 36 hectares is available, the available land would be about 40%. This is unacceptable in general. An alternate plan would be to take into account the total area in such a manner that the machines can be deployed in an orderly manner so that land is used more effectively. In this case, the land that cannot be utilized for wind farming really becomes much less, as can be seen.



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Area lost due to setoffs while windfarming

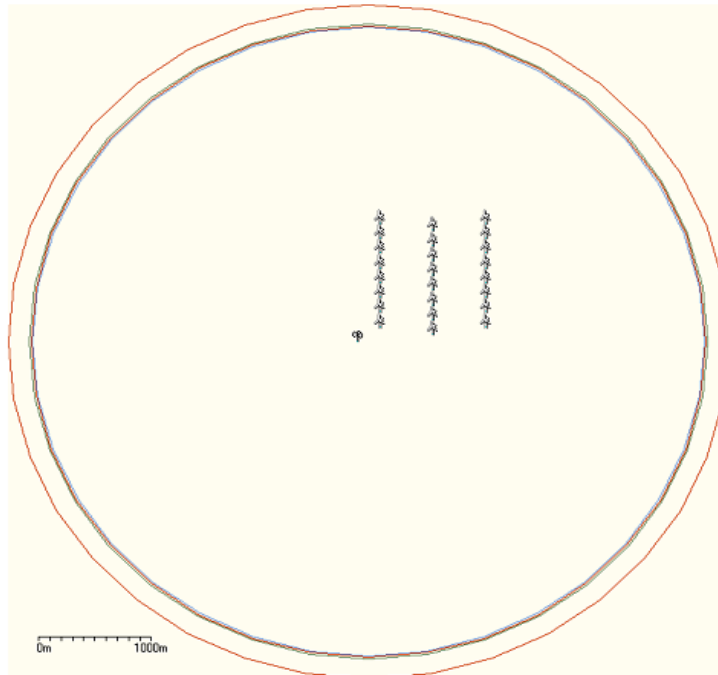
Holding	Tot Area	Net area	% loss
A1	281	185	34.3
A2	194	140	27.9
A3	453	323	28.8
A4	379	283	25.4
A5	274	194	29.3
A6	36	16	56.7
A7	194	126	35.1
Total	1811	1265	30.1

Area in hectares

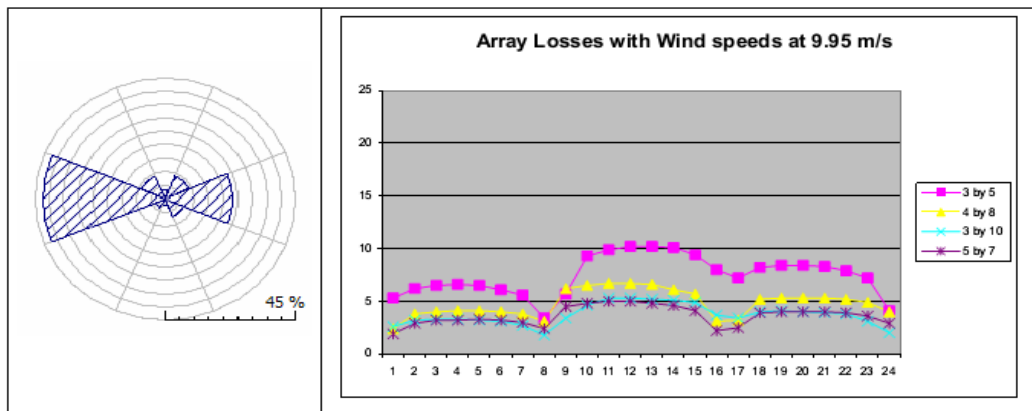
Appendix II

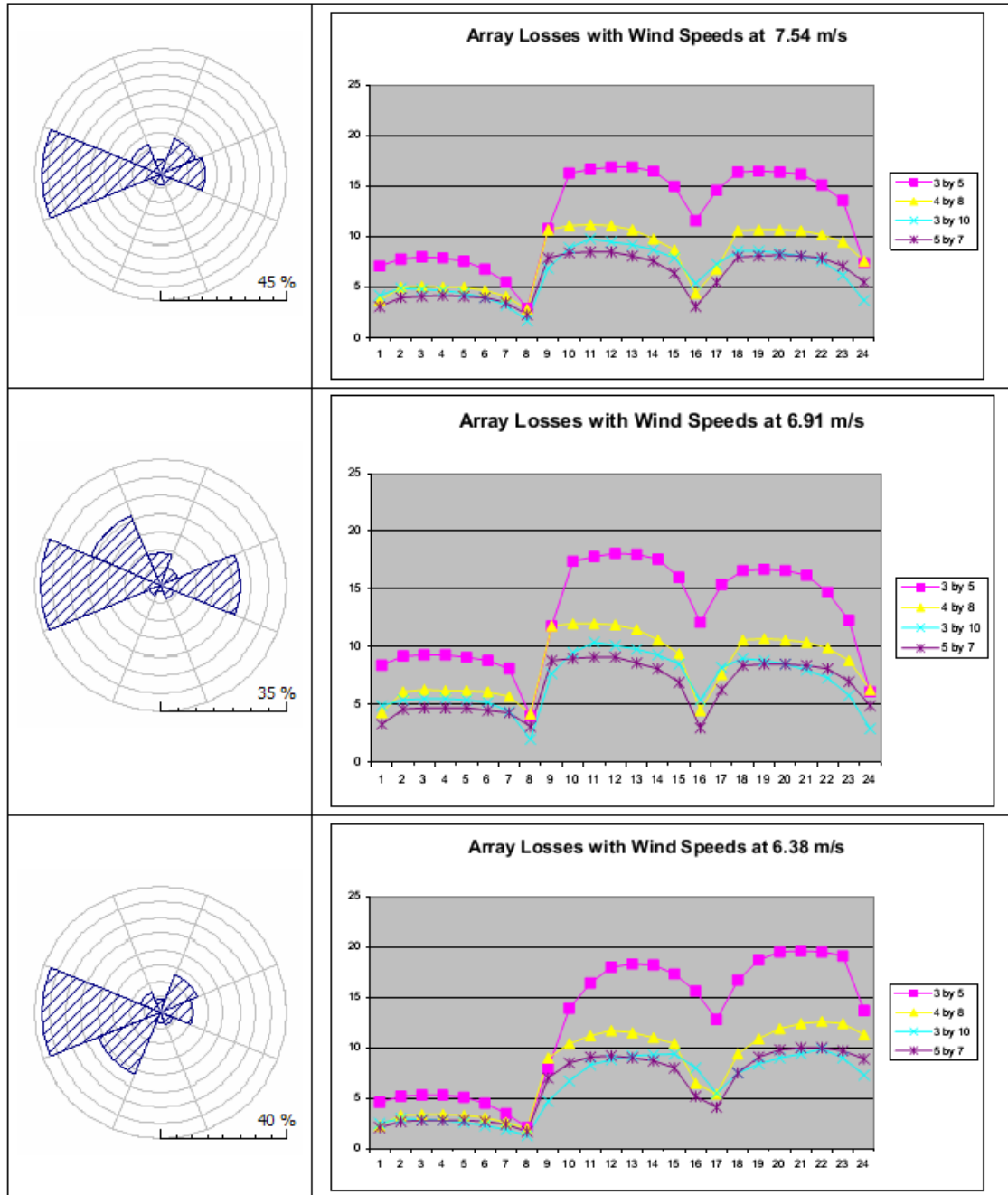
Some typical results of detailed calculations

The outputs from a typical micrositing analysis have been presented below to demonstrate the array effects. The basic premise is to set up a wind farm consisting of twenty-four wind turbines in three rows in an open flat terrain and different wind regimes with consistently westerly winds.



Wind farm under study





It may be observed that

The array efficiencies are less sensitive to inter-machine distances.

The drop in generation appears to be saturating quickly in the rear rows

With moderate wind environment, the array losses can be very significant.

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Table I gives the details of overall array losses in the four wind regimes.

Table 1 Generation as a function of Spacing and wind regime					
	Land required (hectares)	84.5	180.3	169	197
	Land per MW	5.33	11.38	10.67	12.44
Winds ↓ ↓	Array >>	3D by 5D	4D by 8D	3D by 10D	5D by 7D
(m/s)					
9.95	Gross	78.139	78.293	78.108	78.487
	Net	72.333	74.537	75.212	75.644
	% loss	7.43	4.80	3.71	3.62
7.54	Gross	48.127	48.284	48.061	48.496
	Net	42.205	44.388	44.88	45.487
	% loss	12.30	8.07	6.62	6.20
7.19	Gross	45.517	45.639	45.47	45.813
	Net	38.466	41.214	40.938	42.17
	% loss	15.49	9.70	9.97	7.95
6.91	Gross	43.081	43.213	43.017	43.405
	Net	35.903	37.843	38.326	38.84
	% loss	16.66	12.43	10.90	10.52
6.38	Gross	37.056	37.142	36.999	37.289
	Net	32.42	34.192	34.693	34.9
	% loss	12.51	7.94	6.23	6.41

Table 2 Effect of Spacing and Wind Speeds on Generation					
Generation figures in million kWh/year					
Spacing	HH W.S.>>	9.95	7.54	6.91	6.38
3 by 5	Maximum	3.17	2.06	1.75	1.54
	Minimum	2.92	1.73	1.47	1.24
	% Diff.	8.74	19.24	19.29	24.19
4 by 8	Maximum	3.19	2.07	1.75	1.54
	Minimum	3.04	1.85	1.57	1.35
	% Diff.	5.01	11.77	11.47	14.42
3 by 10	Maximum	3.23	2.09	1.79	1.55
	Minimum	3.07	1.87	1.59	1.38
	% Diff.	5.01	11.59	11.98	11.78
5 by 7	Maximum	3.23	2.09	1.78	1.55
	Minimum	3.09	1.91	1.63	1.39
	% Diff.	4.50	9.16	9.15	11.62

Table 2 gives the details of difference between highest and lowest producing wind turbines in the wind farm. As can be seen the maximum losses are suffered under low wind regimes.

The specific outputs obtained from different wind farm configurations on a per MW basis and per hectare basis is presented in table 3.

The four array spacing considered

Table 3 Specific Outputs					
	W.Spdm/s	3 by 5	4 by 8	3 by 10	5 by 7
Output in	9.95	45.66	47.06	47.48	47.76
lakh kWH	7.54	26.64	28.02	28.33	28.72
per MW	7.19	24.28	26.02	25.84	26.62
	6.91	22.67	23.89	24.20	24.52
	6.38	20.47	21.59	21.90	22.03
Output in	9.95	8.560	4.134	4.450	3.840
lakh kWH	7.54	4.995	2.462	2.656	2.309
per hectare	7.19	5.387	2.531	2.691	2.326
	6.91	5.098	2.397	2.545	2.203
	6.38	4.385	2.060	2.189	1.893

