MAXIMUM YIELD FROM SYMMETRICAL WIND FARM LAYOUTS

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Summary

Two key criteria in wind farm design are the energy yield of the turbines and the environmental impact of the wind farm. While the energy yield determines the economic viability of a project, the success of the planning process and acceptance by the general population hinge on the wind farm's environmental impact.

In landscapes with orderly, cultivated structures, random wind farm layouts are not desired, and the developer will instead be required to design symmetrical wind farm layouts in order to achieve an appealing visual impact. Also, the infrastructure cost for cables and access roads may be less, if the turbines are arranged in a regular array.

In this paper we are presenting a new method that enables the design of symmetrical wind farm layouts without compromising on energy yield. Designed for low computational cost, the method also enables the inclusion in the wind farm design process of additional wind farm design criteria, like the cost of energy or the turbine loading.

1. Introduction

For wind farm sites with spatially varying wind resource, methods with stochastic elements are typically used to optimise the wind farm layout to maximise the energy yield [1-3].

For wind farm sites with low spatial variation in wind resource, a new and faster optimisation method is presented in this paper.

To cut down on the degrees of freedom in the optimisation, symmetrical layouts based on the wind speed and wind direction distribution are used.

The fast optimisation allows new parameters to be introduced into the optimisation such as maximum turbine spacing in the prevailing wind direction in order to minimise the wake effects and loads.

2. Symmetrical Optimisation

2.1 Basic symmetries

The symmetry used in the optimisation is based on units that are aligned in two principal wind directions. The optimisation process maximises the turbine spacing in these two wind directions.

The two principal axes are determined from the energy density calculated for each wind direction sector. This is based on the long term wind speed and direction distribution from a mast on site and the turbine power curve. The two principal axes are then pointing towards the two sectors with the highest energy density. The turbine spacing along the principal axes of a unit is determined by their corresponding energy densities.

The principal axes and the corresponding weights are defining the basic shape of the symmetry unit, see Figure 1.

During the optimisation, the length of the axes are scaled, so that the units are expanded or compressed uniformly in order to place the number of turbines desired inside a specific area, while the aspect ratio of the unit remains the same.

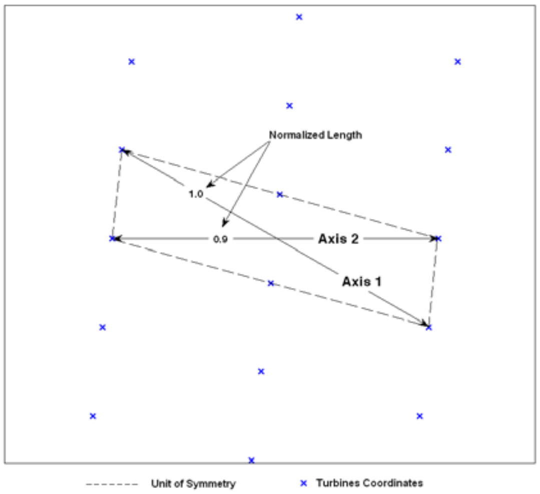


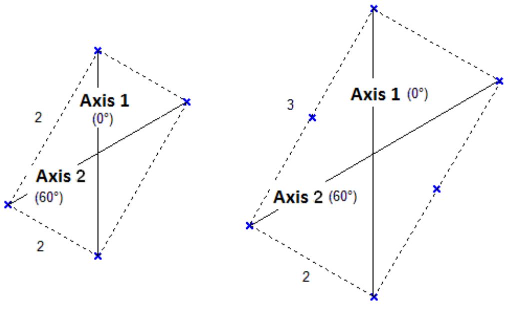
Figure 1: Basic shape of the symmetry unit

2.2 Optimisation

2.2.1 Unit types

A symmetrical unit alternatively consists of 4 turbines with 1 turbine at each corner of the unit ”2-2“ or of 6 turbines with two additional turbines at the center of the longer sides of the unit “3-2”. In the end, the whole layout is composed of such repetitive units. The two unit types are shown in Figure 2.

A 2-2 unit has less turbines per unit and therefore the units need to be smaller (with shorter diagonal spacing in direction of the priority planes) to accommodate a certain number of turbines compared to a 3-2 unit where there are more turbines per unit and they can afford to be bigger (with longer diagonal spacing). On the other hand, a 3-2 unit has less angular freedom than a 2-2 unit because it has turbines at the middle of the longer sides of the unit, for which a certain degree of deviation of the wind direction can cause the middle turbines to be in the wake region of the upwind turbine in the unit.



2-2 Unit

3-2 Unit

Figure 2: 2-2 and 3-2 unit types

It was found that when the angle between the two principal axes are in the order of 30°, a 3-2 unit is beneficial because it allows wider spacing at the shorter side, whereas when the angle is as much as 60° or 90° then a 2-2 unit is better.

2.2.2 Rotation of principal unit axes

A rotation of both principal units is considered. For this the principal axes are rotated, each individually or at the same time, in same or opposite directions. This results in 8 different rotational variations. The variations are detailed in Table 1.

Primary axis	Secondary axis
Clockwise	clockwise
counter clockwise	counter clockwise
counter clockwise	clockwise
Clockwise	counter clockwise
None	counter clockwise
None	clockwise
Clockwise	None
counter clockwise	None

Table 1: Rotation cases

2.2.3 Optimised layout

The symmetric layout optimisation is using a deterministic algorithm where a discrete number of cases are investigated and the layout with the maximum energy yield selected. With this approach the global maximum may well be missed, however the automatic analysis carried out allows to generate a symmetrical layout with competitive high energy yield very fast.

Other constraints like exclusion zones, noise limits at nearby houses as well as turbine visibility can be considered.

3. Example Optimisations

3.1 Generic 5 by 5 km array with 100 turbines

The symmetrical optimiser has been compared to the results from a stochastic optimiser for an area of 5 by 5 km and 100 turbines. The wind resource is uniform over the whole area and a typical Middle-European wind direction distribution has been assumed. The minimum spacing between the turbines is 4 rotor diameters.

The layout using the stochastic optimiser after 830 iterations is shown in Figure 3. The net energy yield of the wind farm is 926 GWh/year. The array efficiency is 93 %

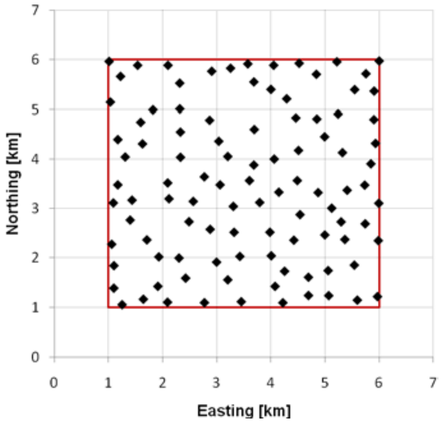


Figure 3: optimised stochastic layout

The best symmetrical layout was found to have the primary axis oriented in a wind direction of 355° and the secondary axis in 205°. The unit type is 3-2. The layout is shown in Figure 4. This layout results in a net energy yield of 917 GWh/year. The array efficiency is 92 %. That means that the net energy is only 1% less than with the optimised stochastic layout.

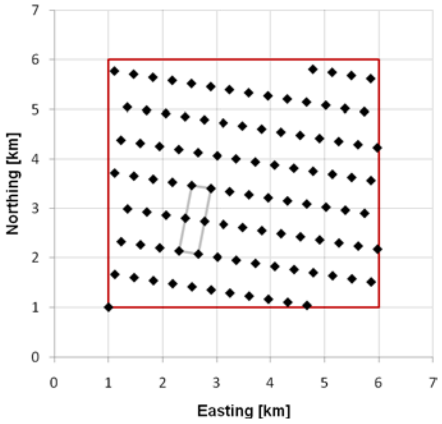


Figure 4: optimised symmetrical layout

Visualisations of the two wind farm layouts are shown in Figure 5 and Figure 6. The view point is located approximately 1.5 km east of the wind farm array.

Figure 5: Visualisation of stochastic wind farm

Figure 6: Visualisation of symmetrical wind farm

3.2 Example Middelgrunden wind farm

The Middelgrunden wind farm is located in the Øresund, 3.5 km outside Copenhagen. It consists of 20 turbines with 80 m rotor diameter. The turbines are arranged in a single curved line. The actual layout is shown in Figure 7.

In the North Sea area the wind direction distribution has strong components from South and West. Operation of the wind farm is thus challenging in cases where the wind blows from North or from South leading to wake losses and increased turbulence levels.

In this demonstration we assume a scenario where the developer has the area indicated by the red line in Figure 7 available for designing the wind farm, uniform wind resource within that area and no further constraints (shipping, fishing, visual, ground condition, etc…) are put on the developer.

In the following we are presenting optimised layouts directly as they are produced by the respective optimisation algorithm without further manual adjustments.

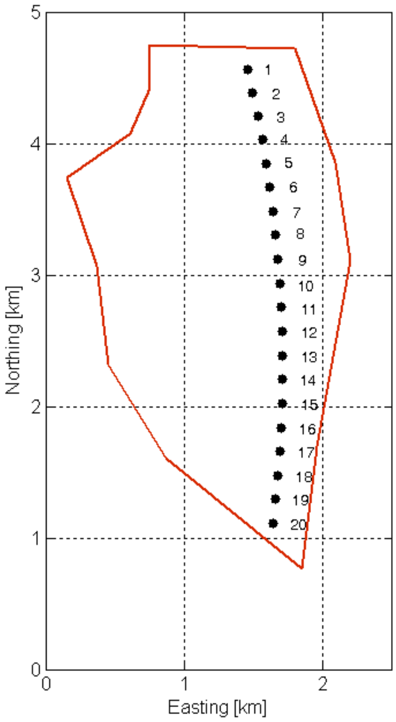


Figure 7: Middelgrunden layout

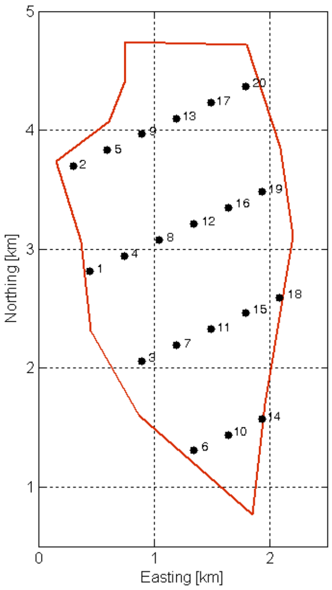


Figure 8: Layout after symmetrical optimisation for Middelgrunden

The resulting layout using the symmetrical optimiser is shown in Figure 8. The primary axis is oriented in a wind direction of 0° and the secondary axis in 160°. The unit type is 3-2. The resulting net energy yield is 105 % of the yield with the actual Middelgrunden layout.

The layout from the stochastic optimiser after 1000 iterations in shown in Figure 9. The resulting net energy yield is 106 % of the yield with the actual Middelgrunden layout.

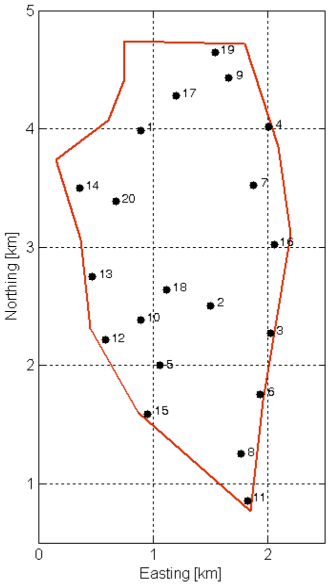


Figure 9: Layout after stochastic optimisation for Middelgrunden

The resulting design equivalent turbulence at 15m/s according to IEC 61400-1 Edition 2 was calculated for all turbines. Results, relative to the original layout for I15, are shown in Figure 10. The design turbulence for the optimised layouts is significantly lower than for the original layout.

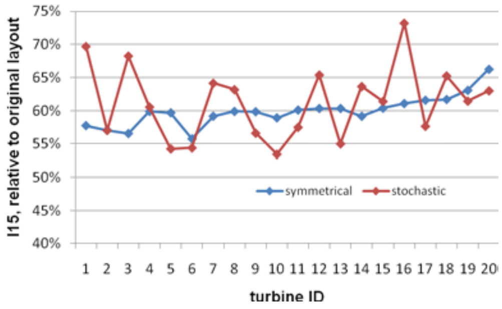


Figure 10: indicative design turbulence (I15) relative to original Middelgrunden layout

4. Conclusions

An algorithm has been demonstrated, that allows the wind farm developer to find a symmetrical wind farm layout with a high energy yield in flat smooth and uniform terrain.

The symmetrical optimiser is very fast, deterministic and requires only a small and finite number of iterations. Resulting layouts are comparable with stochastic layouts with respect to the net energy yield.

The symmetric optimiser typically reduces maximum turbine loads as the minimum inter-turbine spacing is likely to be larger, than for a layout obtained using a stochastic optimisation process.

In some landscapes a developer will be required to design symmetrical wind farm layouts in order to achieve an appealing visual impression of the wind farm. The algorithm presented enables the developer to achieve this very efficiently. The algorithm presented here will soon be available to users of our WindFarmer software.

5. References and Acknowledgements

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The work presented here was funded in part under the EU 6th Framework Program under the contract TREN07/FP6EN/S07/73680/038641 (TOPFARM – Next Generation Design Tool for Optimization of Wind Farm Topology and Operation).