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"Integrated Wind Turbine Design"

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Deliverable D8.6 Lifetime Cost Modelling

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Abstract: An illustrative cost model has been developed to demonstrate the use of lifetime costing in the design of wind farm layouts. This has been combined with a fatigue loads database to show the effect of turbine spacing on loading and hence its potential for use in lifetime cost calculation.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released			**R0**	General public			Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL	**x**			
S4	Under preparation	**x**		**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

The principle goal of the designer of a commercial wind farm will be to make that wind farm as profitable as possible. This is not as straightforward as simply establishing the layout of turbines which generates the highest energy yield. The energy yield represents the income generated by the farm, but to understand its profitability it is also necessary to understand the costs involved in its construction and operation.

Many costs are easy to model – the procurement price of a turbine is a known quantity, for example. Others are much harder to establish. For example, the maintenance cost of a wind farm will depend on many factors, such as the wind conditions, operational strategy, turbine design and build quality and so on.

As part of UPWIND Work Package 8, GL Garrad Hassan have developed a cost model to illustrate how a financial analysis of a wind farm layout should be performed. This cost model considers the lifetime economics of the farm, including both the capital investment and operational costs.

It is aimed at helping the wind farm designer establish the optimum turbine layout. For this reason it can safely be restricted to analysing only those costs which will vary with the layout. The procurement costs of the turbines, for example, have been ignored since for a fixed number of turbines they will not change, regardless of where on the site the turbines are installed.

A central part of this cost model has been to analyse the costs incurred as a result of turbulence induced fatigue loading on the turbines. This is arguably the most complex part of the analysis, since it involves calculation of wake induced turbulence, fatigue loading and consequent repair and maintenance costs.

2. Fatigue loads database

Fatigue damage to wind turbines caused by wake-affected turbulence is a significant factor in the design of wind farm layouts. It affects the cost of energy both directly in terms of maintenance costs, and indirectly by determining the IEC class of turbine which is used on the site.
Currently, industry practice is to assess the extent of fatigue by calculating a *design equivalent turbulence*, in accordance with IEC 614100-1, Annex D [1]. This is based around the 'Frandsen method', and is commonly implemented in wind farm design software such as *WindFarmer*. Calculated equivalent turbulence levels are compared against the envelope of acceptable levels in the IEC classifications, to give a pass/fail determination of whether conditions at a potential turbine location are acceptable.
This conventional approach is limited in the detail which it can determine, and researchers have been investigating potential improvements. One possibility is to quantify the wind conditions which a turbine is expected to experience, and use this as the input to an aero-elastic model such as *Bladed*. This would yield highly detailed results, allowing analysis of the loading on any component in the turbine, but would be very time consuming, requiring several hours of work. It would not be feasible to follow this approach when considering a choice of many possible layouts of a multi-turbine wind farm.
GL Garrad Hassan developed an intermediate approach. The fatigue loads on a turbine under a very wide range of possible wind conditions are pre-calculated using *Bladed*. The results are stored in a *fatigue loads database*. The fatigue loads for a particular wind condition can then be quickly recalled by reading from the database. The process of creating the database is relatively slow, but only needs to be performed once for a given turbine model. The speed of reading from the database makes this initial investment worthwhile.
A research version of *WindFarmer* was written which contains an interface to the loads database. When configured with a turbine layout and ambient wind conditions, *WindFarmer* calculates the incident wind speeds and turbulence intensities, including wake effects. These are used to interrogate the fatigue loads database, which returns the margin between the design and calculated loads for a selection of critical components. It also returns a simple 'pass/fail' flag, which indicates when loads exceed their design limit.
An example of the output available from the loads database is shown in Table 1 below. Results for six turbines in a single wind farm are given. Data represents the margin between the calculated fatigue load and the design load, as a percentage. A negative value indicates that the calculated load exceeds the design load.

Turbine ID	Load Test	Blade root Mx (%)	Blade root My (%)	Rev at level (%)	Tower top Fx (%)	Yaw bearing Mz (%)	Stationary Hub My (%)
1	pass	3.2	2.1	5.1	8.7	8.1	8.1
2	fail	1.0	-4.9	3.8	-0.3	-0.8	0.2
3	pass	3.0	5.4	2.9	9.9	9.0	8.7
4	pass	4.3	7.1	4.6	14.4	13.4	12.8
5	fail	2.9	-0.6	6.8	6.4	6.0	6.8
6	pass	4.3	5.0	7.7	12.6	12.3	12.4

Table 1 . Example output from fatigue loads database

3. Cost Model

A cost model is required to establish the economics of a wind farm.
A wide variety of different costs is incurred during the lifetime of a wind farm. They can be broken down into capital costs such as turbine purchase and installation; and operational costs such as repairs and maintenance.
It should be remembered that ultimately the design must also have a low enough environmental impact to gain planning permission. It is difficult to apply a quantitative analysis to environmental impact, and so no attempt has been made here. The assumption is made that only layouts which meet environmental constraints will be subject to a financial analysis.
An alternative to profit as a measure of the quality of a wind farm design is the Cost of Energy. This measure was described by the IEA [2], and is also sometimes referred to 'levelised production costs':

$$CoE = \frac{\sum\left[(I_t + M_t + F_t)(1+r)^{-t}\right]}{\sum\left[E_t(1+r)^{-t}\right]}$$

Where: CoE = Lifetime levelised Cost of Energy
I_t = Investment expenditures (capital costs) in the year t
M_t = Operations and maintenance (O&M) expenditures in the year t
F_t = Fuel expenditures in the year t
E_t = Electricity generation in the year t
r = Discount rate

The Cost of Energy is calculated over the economic lifetime of the project, typically 20 years. Since wind power is a renewable energy source, the fuel costs can be considered to be zero, and ignored.
For a wind farm with a given number of turbines of a given model, the aim of the designer will be to establish the turbine layout with the lowest Cost of Energy.
Costs, whether they are capital or O&M, can usefully be divided into those which are fixed regardless of the turbine locations, and those which will vary. Fixed costs would include items such as the capital cost of the turbines, and routine maintenance. Variable costs would include items such as the infrastructure connecting turbines, and damage caused by excessive fatigue. The fixed costs will not influence the optimiser's choice of turbine locations, and so can safely be ignored. Only the variable costs will be considered in this report.
A cost model has been developed which demonstrates the principles of calculating the Cost of Energy. A great deal more research is required to refine this model to the point where it produces reliable and generally applicable results, but it serves to illustrate how such a model might be used to aid the wind farm designer.
The model considers a sample set of the most significant variable costs. These are:

- Civil and electrical infrastructure (capital cost)
- Fatigue induced maintenance (O & M cost)

These are combined year by year with the energy yield, on a discounted basis, to give a lifetime Cost of Energy. The flow of data through the cost model is shown in Figure 1 below.

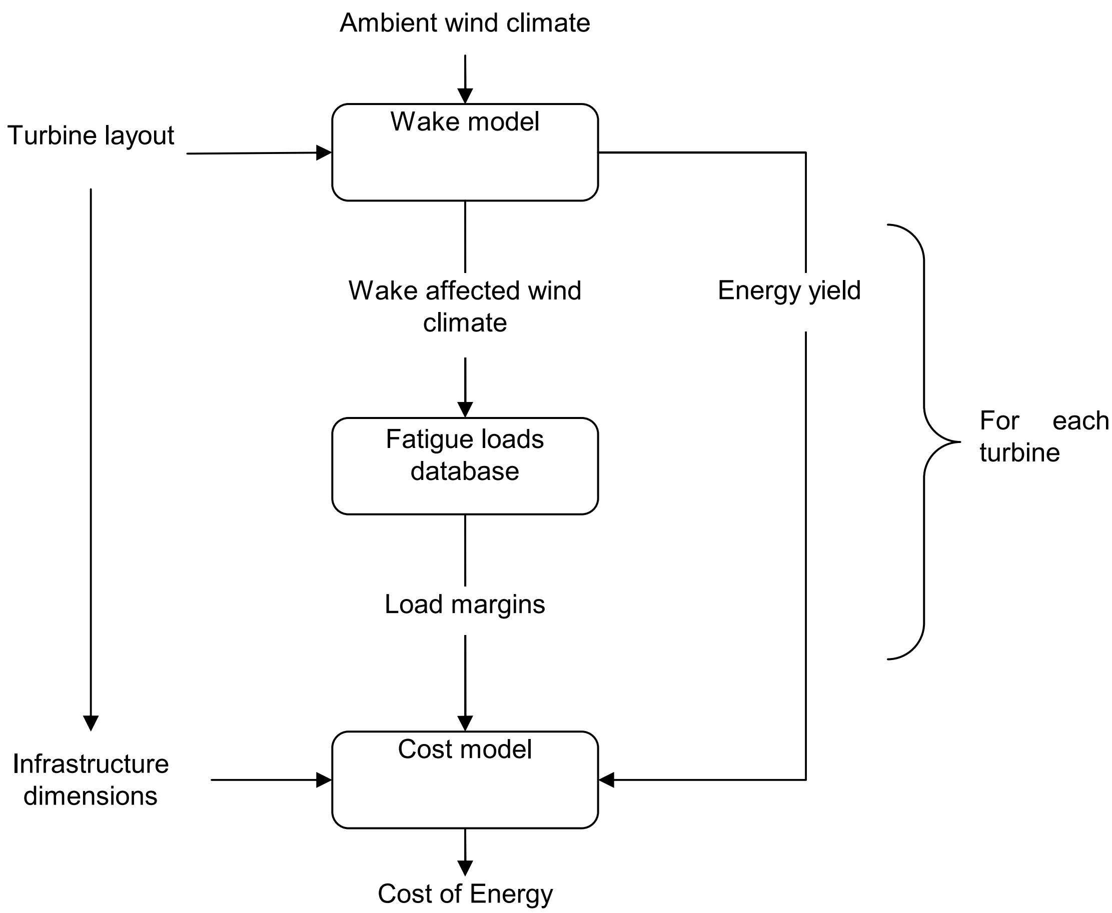

Figure 1. Cost model structure

3.1 Civil and electrical infrastructure

Any wind farm will require a network of electrical cabling to be installed between the turbines and the point of common connection with the electrical grid. Onshore wind farms can also be expected to require access tracks to be built to turbines.

The cost of this infrastructure is a significant part of the capital cost of a wind farm, and can vary considerably with the layout of the turbines. Attempting to calculate it automatically from an arbitrary layout of turbines is challenging, as the model is required to determine what route the tracks and cables would follow. This is a variation of the classic 'travelling salesman' problem which, while solvable, is computationally intensive.

Constraining the layout to a regular, 'symmetrical', grid makes this problem considerably easier. Tracks and cables can be assumed to run in straight lines along rows, and calculation of their length becomes trivial. The cost can then be calculated by simply multiplying the length by a cost per meter factor. This constraint is assumed for this illustrative cost model.

3.2 Fatigue induced maintenance

Turbulence in the wind induces fatigue in the components of a turbine, and high levels of fatigue can be expected to cause components to fail. Repair of failed components is a cost which contributes to the overall Cost of Energy.

The fatigue loads database described in section 2 can be used to quantify the margin between the design loads and site specific loads for critical components in a turbine. Where a site specific load exceeds the design load, that particular site can be considered unacceptable for a turbine.

Where the site specific load is less than the design load, the site is acceptable, and is suitable for financial modelling. A probabilistic approach is taken, analysing every critical component of every turbine in the wind farm. The size of the margin between the loads can be considered to determine the probability of failure of that particular component. The probability of failure in any given year multiplied by the cost of repair gives the annual maintenance cost for each component.

Further research is required to establish precisely what probability distribution should be used for this modelling. The conclusions are unlikely to be straightforward, and can be expected to differ for each component. For this illustrative cost model, a log-normal distribution has been assumed, but it should be emphasised that this is for illustrative purposes only. The load margin is used to scale the mean component lifetime, such that a positive margin results in an increased mean lifetime.

Figure 2 shows how this model predicts an increasing probability of component failure with the age of the turbine.

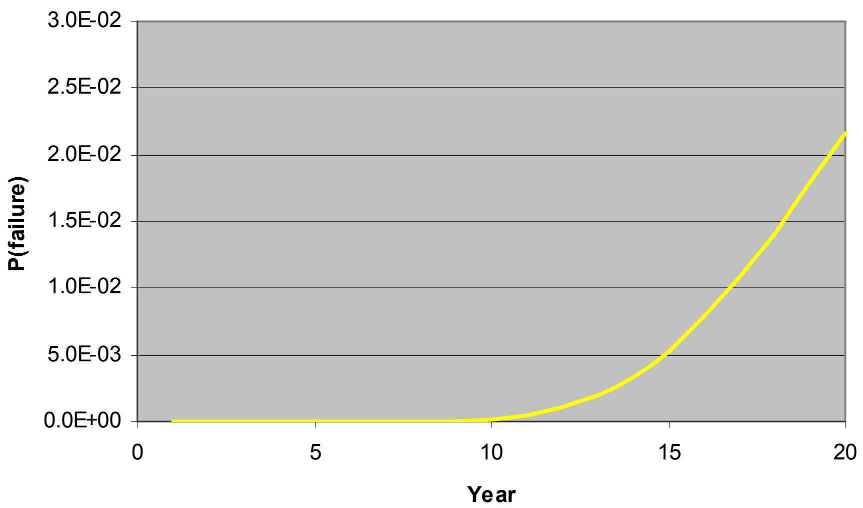

Figure 2. Increasing probability of failure with age

4. Example Optimisations

To demonstrate the use of Cost of Energy in establishing the optimum layout of turbines, two example optimisations have been performed:

- In a uniform, unidirectional wind climate
- On a hill top, with higher wind speeds at the top of the hill

The simplest possible wind farm has been modelled: two turbines of the same type. In this case, a generic 2MW, 80m diameter turbine has been studied.
The separation between the turbines has been varied. *WindFarmer* software has been used to calculate the wake effects, with resultant loss of wind speed and increase in turbulence at the downwind turbine, and consequent energy yields from the turbines.
The wind conditions modelled by *WindFarmer* were used to index the fatigue loads database, which output the margins on six key loads. This data was input to the cost model, which calculated probability of failures and cost of repair. These are the only operational costs considered by this cost model.
The cost model also calculated the capital cost of civil and electrical infrastructure, by applying a simple cost per meter figure to the separation distance between the two turbines. These are the only capital costs considered by this cost model.
Throughout the following discussion, only costs which vary with turbine layout are considered. A great many other costs are, of course, incurred but these would not affect the choice of turbine layout, and so are not considered here.
Key assumptions made in this implementation of the cost model are detailed in Appendix 1. It should be remembered that these assumptions, and the results drawn from them, are purely for illustration and should not be considered authoritative.

4.1 Uniform wind climate

In this example, a simplistic wind regime has been assumed:

- Mean hub height wind speed: 8m/s
- Uniform ambient wind conditions across the site
- Unidirectional wind flow directly between the two turbines

The two turbines were modelled such that one was directly downwind of the other, as shown in Figure 3. In this situation, the wind incident on the upwind turbine will be unaffected by the separation distance of the two turbines.

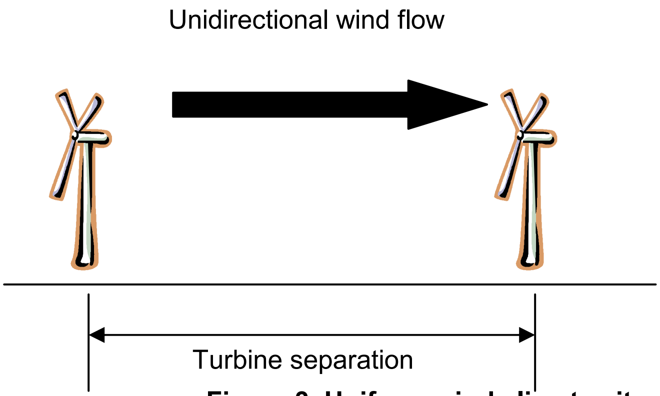

Figure 3. Uniform wind climate site

The *WindFarmer* model showed that, as can be expected, the mean wind speed incident on the downwind turbine increases as the turbines are moved further apart. This is because it is directly in the wake of the upwind turbine – increasing the separation decreases the wake, and so increases the mean wind speed. This increased wind speed generated a corresponding increase in energy yield, as shown in Figure 4.

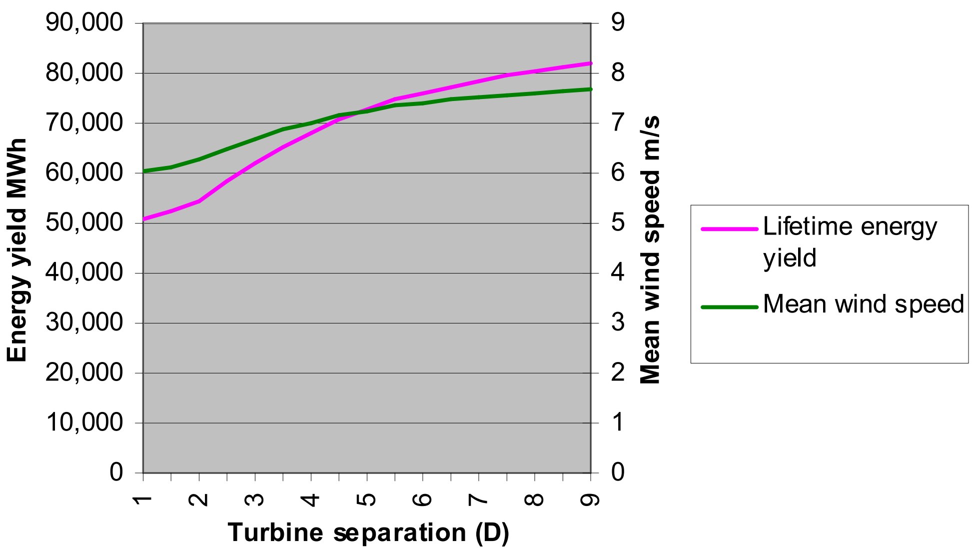

Figure 4. Variation in wind speed and energy yield

Energy yield goes on increasing with increased separation, but in practice the rate of increase has more or less flattened out once a separation of 10D has been reached.
Increasing turbine separation also causes a reduction in turbulence intensity. This was quantified here by reading the load margins from the fatigue loads database. The cost model converted this into a total lifetime cost for repairs and maintenance. This is shown in Figure 5, together with an example load margin – that for the blade root M_y.

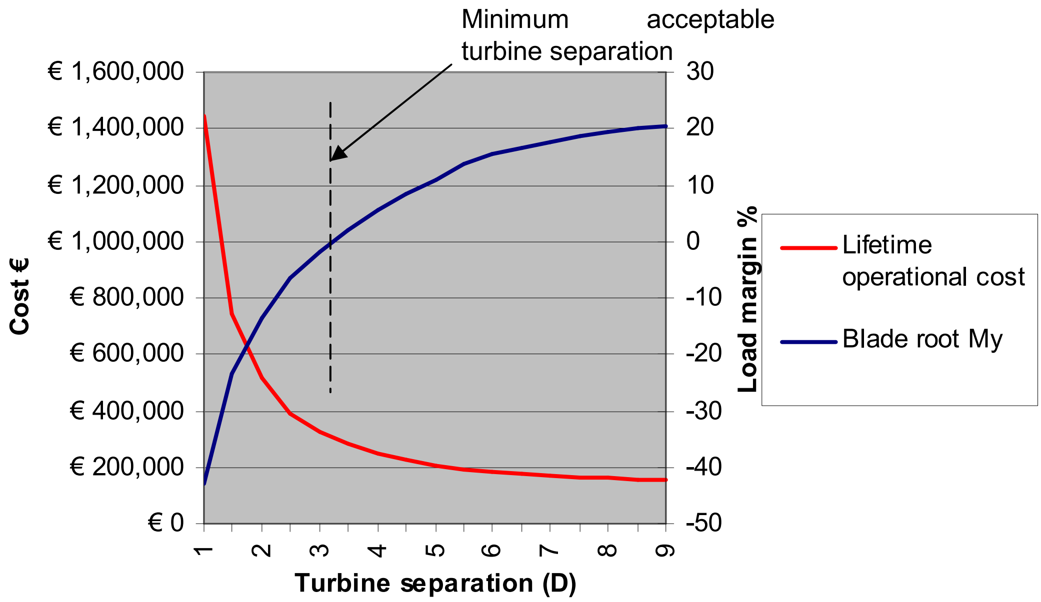

Figure 5. Variation in loading and operational cost

It can be seen that at small separation distances the margin for the loading on the blade is below zero. This indicates that the fatigue loads will exceed the design limits, and in practice it would be unacceptable to place turbines with such a small separation. In this case, the minimum separation is around 3.5D.

As with energy yield, operational costs continue to improve as turbines are spaced further apart. However, capital costs, here determined by the infrastructure connecting the two turbines, increase as turbine spacing increases. When these are added to the operational costs to give the lifetime total costs, there is a separation distance at which the total costs are at a minimum. This can be seen in Figure 6. In this case, the minimum cost occurs at a separation distance of approximately 6D.

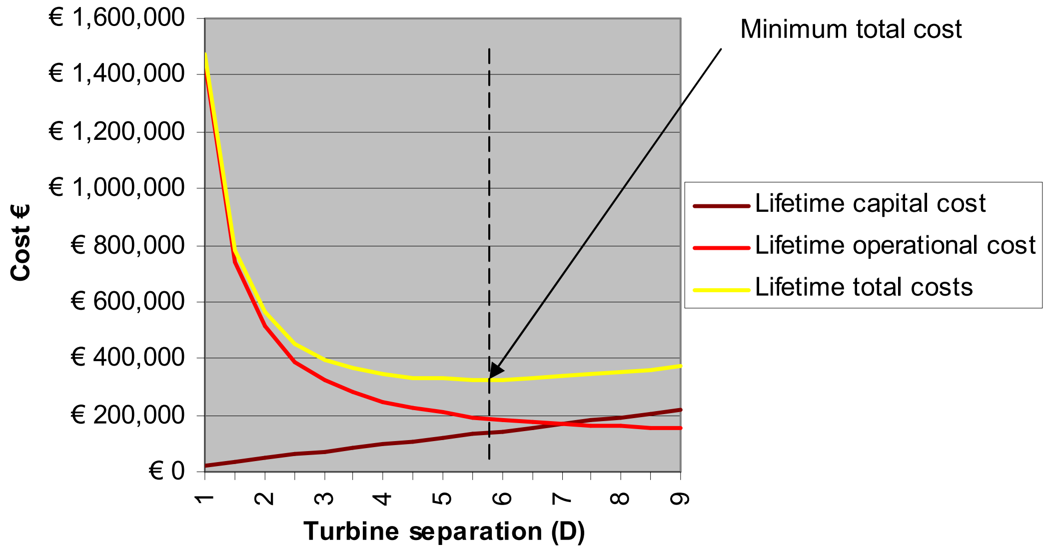

Figure 6. Variation of costs with separation distance

The separation with the minimum total cost will not represent the optimum separation distance. This is found at the minimum Cost of Energy. Figure 7 shows the result of combining the total cost with the lifetime energy yield, to give the Cost of Energy.

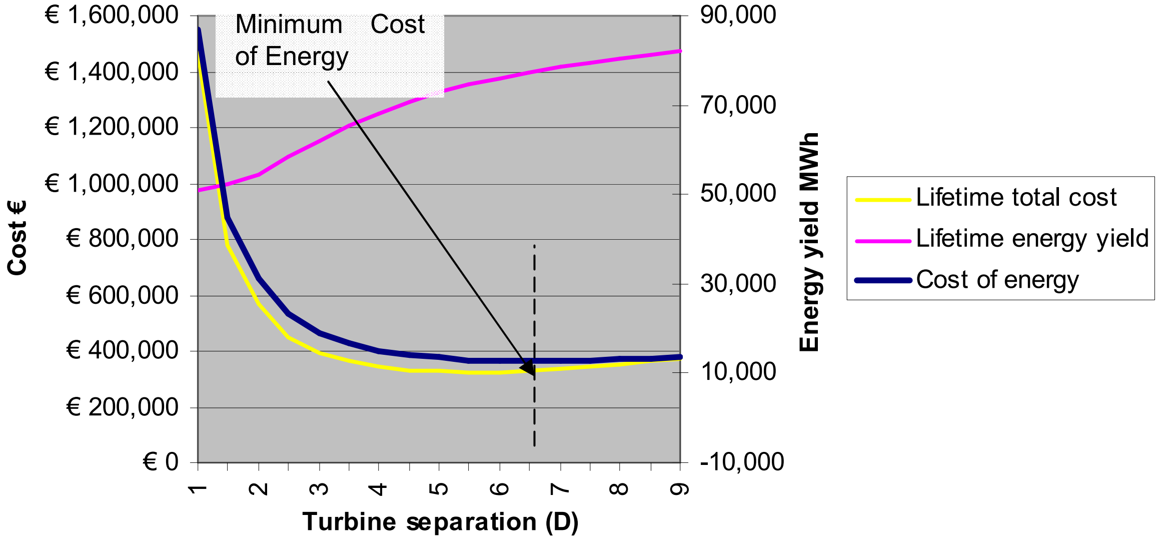

Figure 7. Variation of Cost of Energy with separation distance

It can be seen that the minimum Cost of Energy, and hence the optimum turbine separation distance, in this simple case occurs at around 6.5D.

4.2 Hilltop wind regime

In this example, two turbines were placed in a more realistic situation, as shown in Figure 8. Notably:

- Wind speed was highest at the top of the hill

- Wind rose was varied, but one turbine was downwind of the other in the prevailing wind direction

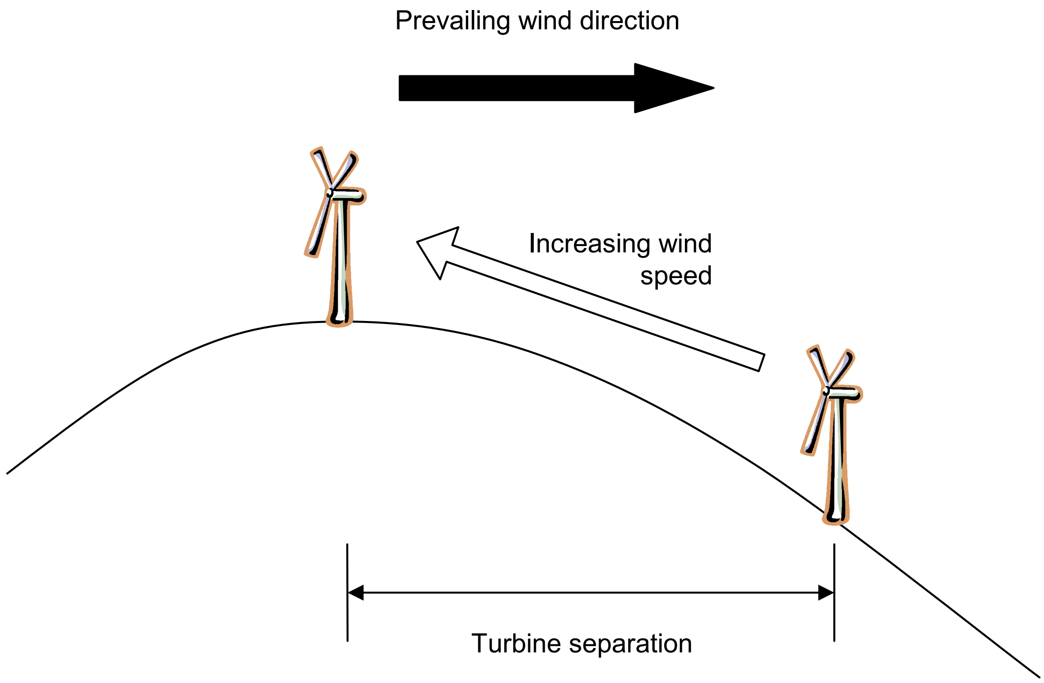

Figure 8. Hilltop site

For these tests, the upwind turbine remained in a fixed location at the top of the hill, and the downwind turbine was moved further away. This moved it down the hill, into decreasing wind speeds, as can be seen in Figure 9. Wrinkles in the curves are caused by irregular terrain. This effect worked contrarily to the decrease in wake loss with increasing distance, and resulted in a maximum incident wind speed and energy yield at a separation of around 5D. This is the separation which can be expected to result from the use of a conventional layout optimiser. Note that the maximum at 2D has been ignored here because loads exceed the design limit.

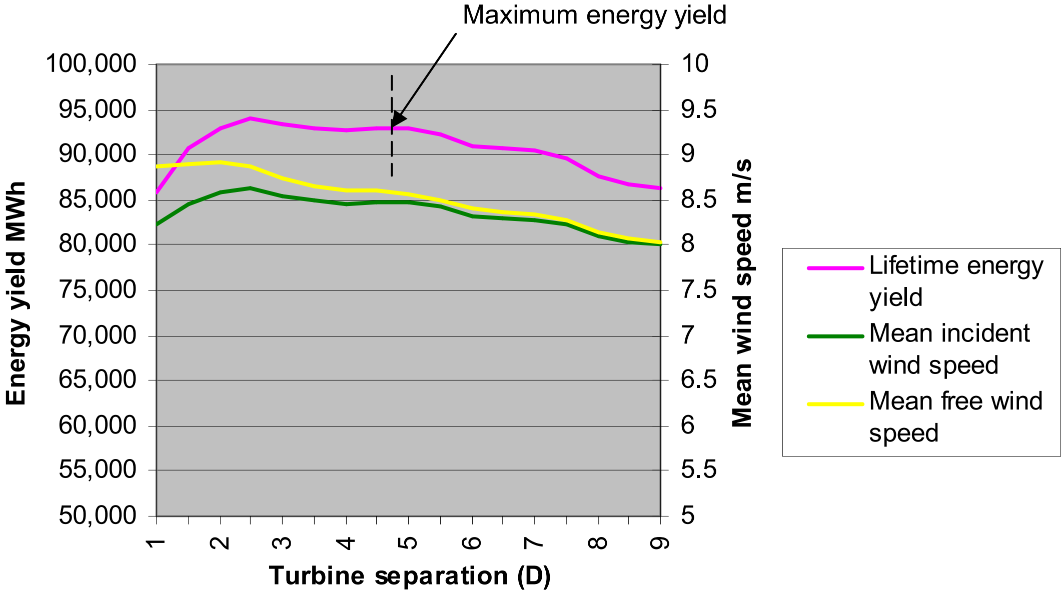

Figure 9. Variation in wind speed and energy yield

The energy yield was combined with the lifetime capital and operational costs to determine the Cost of Energy curve. As Figure 10 shows, this reaches a minimum at a turbine spacing of around 4.5D – this will be the optimum spacing in this example.

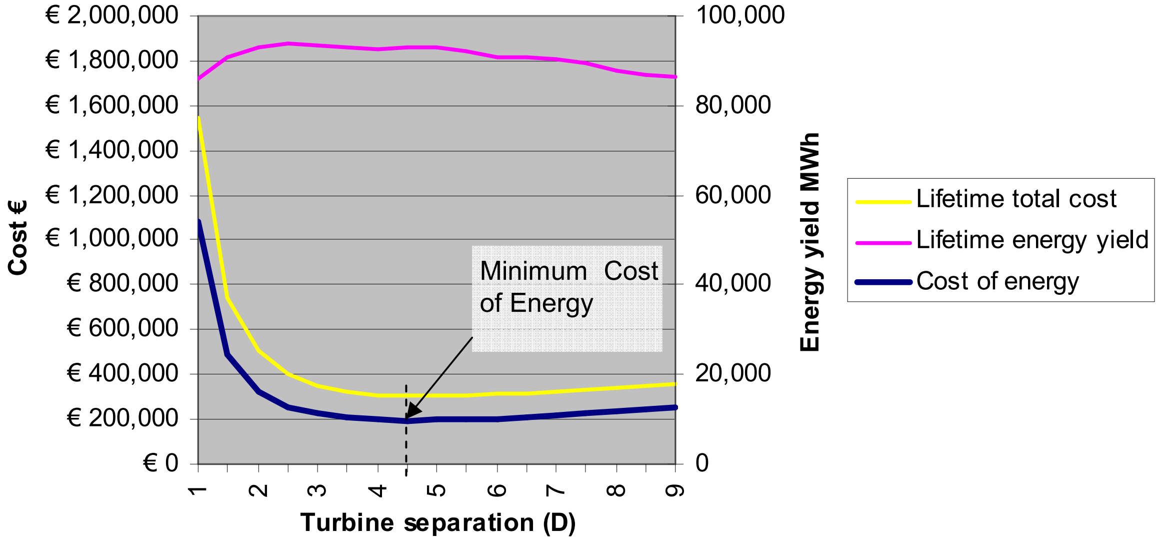

Figure 10. Variation in Cost of Energy

5. Conclusion

This work has shown an approach for establishing an optimum turbine layout based on economic performance. This represents an improvement on conventional optimisers which target maximum energy yield.

Costs which vary with turbine layout, both capital and infrastructure, have been included in the cost model. Development of the fatigue loads database has created a technique for rapidly establishing the site specific loading on critical components, at speeds which are fast enough to be usable in an optimisation routine.

Preliminary testing has shown that the use of Cost of Energy as the target for layout optimisation gives different results from the use of energy yield. This will be valuable to wind farm developers, for whom economic performance is ultimately of prime importance.

Considerable further work is required to refine the cost model. Its structure is currently purely illustrative. The process of establishing the relationship between maintenance costs and fatigue loading in particular is currently little understood, and needs to be further investigated.

6. REFERENCES

1. International Electrotechnical Committee, *IEC 61400-1: Wind Turbines Part 1: Design Requirements*, 2005

2. IEA, OECD, NEA, *Projected Costs of Energy*, 2005 Update.

Appendix A: Key assumptions of the cost model

The assumptions made here are purely to illustrate the functioning of the cost model. Values used are illustrative only, and should not be considered to be authoritative.

Financial assumptions

- Project lifetime: 20 years
- Discount rate: 5%

Cost assumptions

- Infrastructure cost: €300/m
- Tower replacement cost: €2,400,000
- Blade replacement cost: €700,000
- Hub replacement cost: €700,000
- Gearbox replacement cost: €500,000
- Yaw system replacement cost: €80,000