



A guide to calculating the carbon dioxide debt  
and payback time for wind farms

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August 2006

The Renewable Energy Foundation is willing to check calculations made by individuals or groups on the basis of the information presented in this paper before their formal submission to local authorities or Public Inquiries.

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A wind turbine base at Cefn Croes, Wales, showing steel reinforcing bars and collar in place prior to pouring concrete. Note the two-metre deep peat cut through at the rear.

### Why is payback time important?

Apart from providing electricity, the government sees wind farms as an important mechanism for reducing the UK's carbon dioxide (CO<sub>2</sub>) emissions. Their contribution to combating climate change is often advanced by wind-power developers and their advocates as a major argument for approving planning applications.

As with any manufacturing process, building and erecting the turbines creates CO<sub>2</sub> emissions and a wind farm must pay back its CO<sub>2</sub> 'debt' before it can claim to contribute to these national objectives. It is obviously vital that this debt is known and considered at the planning stage.

This guide examines aspects of the contribution made by wind farms to reducing CO<sub>2</sub> emissions. As well as estimating the CO<sub>2</sub> emitted during the construction phase, it considers the longer-term accrued emissions debt arising from the impact of a wind farm on its location.

This will vary considerably from site to site. A wind farm on a grassland site in southern England may have a relatively low debt and short payback time whilst one built on a peat-rich blanket bog will have a much higher debt and longer payback time.

### What is a carbon dioxide debt?

It is broadly accepted that wind turbines do not emit CO<sub>2</sub> at the point of generation. However, in common with all types of power station, it is emitted during their construction and, through damage directly inflicted on the construction site, over a much longer period. The total debt will vary from site to site but will comprise some or all of the following;

- Emissions arising from fabrication (steel smelting, forging of turbine columns, the manufacture of blades and the electrical and mechanical components);
- Emissions arising from construction (transportation of components, quarrying, building foundations, access tracks and hard standings, commissioning);
- The indirect loss of CO<sub>2</sub> uptake (fixation) by plants originally on the surface of the site but obliterated by construction activity including the destruction of active bog plants on wet sites and deforestation;
- Emissions due to the indirect, long-term liberation of CO<sub>2</sub> from carbon stored in peat due to drying and oxidation processes caused by construction of the site.

It is important to recognise that peat is a major store of carbon accumulated from dead plant remains over many millennia. It is held in perpetuity because the bog's wetness and acid conditions prevent the access of oxygen and inhibit the growth of bacteria which would otherwise rot the vegetation. Draining peat for construction reverses both these long-term processes: the soil is exposed to the air, the carbon is converted to CO<sub>2</sub> and released slowly to the atmosphere.

Several papers from the wind industry in Denmark and the UK have addressed the first two points with estimates of payback time ranging from about six to 30 months.

However, the industry rarely, if ever, considers the last two. This is a fundamental omission as their contribution to the overall CO<sub>2</sub> debt, in particular the last, can be far greater than all the others put together. This paper outlines a procedure for quantifying it.

## The purpose of this guide

The guide has been prepared to enable anyone with access to the Environmental Statement (ES) that forms part of a Planning Application (PA) for a wind farm to estimate its CO<sub>2</sub> debt. (If some of the requisite information proves to be unavailable, this ought to provide grounds for postponing consideration of the application and the commissioning of further assessment.)

The results of the calculations described should be submitted to planning authorities or Public Inquiries as part of the arguments used in assessing the merits and demerits of an application.

## Calculating total CO<sub>2</sub> debt and site payback time

Set out below are:

- a list of the variables and constants required to carry out the calculation;
- a worked example (Whinash windfarm, Cumbria) using data from its PA, Environmental Impact Assessment (EIA) and ES;
- details of a spreadsheet which automatically calculates payback time given the site-specific data. It also allows you to explore the effect of turbine size, load factor, peat depth, etc on payback times.

The calculations are based on three scenarios derived from a detailed study by Richard Lindsay of the EIA that accompanied AMEC and British Energy's first Lewis Wind Power application.<sup>1</sup> The study was commissioned by the RSPB and is available on its web site.

Lindsay showed that excavations and ditching associated with wind-farm construction cause peat to dry out over time due to a progressive fall in the water table. Once dry, the surface layers of peat oxidise and its stored carbon is converted to CO<sub>2</sub> and released into the atmosphere. This causes a gradual further fall in the water table and the cycle repeats. After some years, the surface level can fall by many feet. He found that ditches could affect the water table as far as 250 metres away on a particularly wet site.

The scenarios used in this calculation are defined as follows:

- The *low scenario* (the one most often used explicitly or implicitly by developers) generally assumes that peat damage occurs only at the site of turbine bases and borrow pits or beneath access tracks and that the damage extends no more than five metres from the sides of these constructions;
- The *medium scenario* allows for damage to peat extending outwards for 50 metres from the sides of turbine bases, access tracks and borrow pits;
- The *high scenario* allows for damage to peat extending outwards for 100 metres from the sides of turbine bases, access tracks and borrow pits.

On typical lowland sites devoid of peat, the low scenario would apply. For many upland sites on dry or shallow peat, the medium scenario best describes how the peat might behave over time while for wet, peat-rich sites with active blanket bog, the high is more likely. Knowledge of the site under consideration should guide you to the most likely scenario. Local Wildlife Trust or nature conservation groups should be able to advise.

The calculations are *not* detailed or absolute forecasts of how a given site will behave following intrusive construction activity but are, rather, approximate quantifications based on well-understood properties of peat soils, recognised constants and conversion factors and industry-standard publications.

<sup>1</sup> Lindsay, *Lewis Wind Farm Proposals: observations on the Environmental Impact Statement*, RSPB, May 2005.

## Performing the calculation

The following information is needed. Some factors vary from site to site but others are constant.<sup>2</sup> The site dependent factors are:

- The number and installed capacity of the turbines
- The claimed load (or capacity) factor
- The size of the turbine bases, hard standings and quarries ('borrow pits')
- The length, width and depth of the aggregate laid for access tracks
- The width of any drainage ditches cut alongside the access tracks
- The extent of tree felling, if applicable
- The average depth of peat on the site.

The above should all be available in the Environmental Statement. Constants applicable to all sites are:

- The number of hours in a year (8,760)
- The carbon fixed by growing bog (19 gm/m<sup>2</sup>/year)
- The mass conversion factor, carbon to CO<sub>2</sub> (multiply by 44 and divide by 12)
- The carbon content of dry peat (55 kg/m<sup>3</sup>)
- The weight of rock used for access tracks and ballast (2 t/m<sup>3</sup>)
- CO<sub>2</sub> displaced at a power station by wind-power generation (0.43 tCO<sub>2</sub>/MWh)<sup>3</sup>
- CO<sub>2</sub> emitted by quarrying and crushing rock (0.2 tCO<sub>2</sub>/m<sup>3</sup>)
- CO<sub>2</sub> emitted during turbine manufacture (1,189 tCO<sub>2</sub>/MW turbine capacity)
- CO<sub>2</sub> emitted per 15 m x 15 m x 1.5 m turbine base (248 tonnes/base) (includes cement, aggregate, steel, rock and sand)

Appendix 2 explains how some of these were derived. The others are deemed non-controversial.

<sup>2</sup> Installed capacity is measured in megawatts (MW), electrical production in megawatt hours (MWh), length in metres (m), area in square metres (m<sup>2</sup>) or hectares (1 hectare = 10,000 m<sup>2</sup>) and weight in grammes, kilogrammes and tonnes. Load Factor (LF) or Capacity Factor (CF) is the expected annual electricity output as a percentage of the maximum theoretically possible; tCO<sub>2</sub> = tonnes of CO<sub>2</sub>. Thus, tCO<sub>2</sub>/MWh = tonnes of CO<sub>2</sub> per megawatt hour and so on.

<sup>3</sup> Many planning applications use a figure twice this (0.86 tCO<sub>2</sub>/MWh) but this is no longer held by the government to be correct, a view endorsed by a ruling by the Advertising Standards Authority in December 2005 – details from REF on request. Any use of the higher figure should be challenged.

**A worked example:****Calculating CO<sub>2</sub> payback time for the Whinash wind farm**

The Whinash site, which was refused consent following a Public Inquiry in 2006, would have occupied a rounded ridge between the Lake District and Yorkshire Dales National Parks. The total area of 763 hectares is composed of blanket bog in relatively poor condition, purple moor grass/rush pastures and upland heath. Compared to many sites in Wales and Scotland, it has a shallow peat covering and patchy areas of blanket bog. It is deemed to be a *medium* scenario site and the extent of peat degradation is thus assumed to be 50 metres. The data below are taken from the developer's PA, ES and Supplementary Environmental Information.

Number of turbines	=	27
Installed capacity per turbine	=	2.5 MW
Total installed capacity	=	27 x 2.5 = 67.5 MW
Anticipated load factor	=	35%
Thus, electricity generated	=	67.5 MW x 8,760 hours/year x 35% = 206,955 MWh/year
and CO <sub>2</sub> 'saving'	=	206,955 x 0.43 t/MWh = 88,990 t/year
Access tracks	=	16.7 km long x 5 m wide x 0.5 m deep
Average peat depth	=	0.48 metres (rounded to 0.5 m)
Site lifetime	=	25 years

**How much CO<sub>2</sub> would be emitted by the project?****CO<sub>2</sub> emitted as a result of deforestation**

CO<sub>2</sub> emitted = None. No tree felling would have been necessary at Whinash – but see Appendix 1

**CO<sub>2</sub> emitted during fabrication, transport and assembly of turbines**

CO<sub>2</sub> emitted = 1,189 t/MW x 27 x 2.5 = 80,258 tonnes

**CO<sub>2</sub> emitted during manufacture of turbine bases**

CO<sub>2</sub> emitted = 248 tCO<sub>2</sub>/base x 27 = 6,696 tonnes

**CO<sub>2</sub> emitted by quarrying and crushing aggregate for access tracks and turbine bases**

volume of access tracks = 16,700 m x 5 m x 0.5 m = 41,750 m<sup>3</sup>  
 volume of base ballast = 500 m<sup>3</sup>/base x 27 = 13,500 m<sup>3</sup>  
 volume of hard standings = 50 m x 20 m x 0.5 m x 27 = 13,500 m<sup>3</sup>  
 thus, total aggregate volume = (41,750 + 13,500 + 13,500) = 68,750 m<sup>3</sup>  
 and CO<sub>2</sub> emitted = 68,750 x 0.2 tCO<sub>2</sub>/m<sup>3</sup> = 13,750 tonnes

**CO<sub>2</sub> emitted due to loss of fixation by damaged bog**

The low scenario is always applied to calculation of fixation loss. The area of bog surface lost is as follows:

$$\begin{aligned}
 \text{weighted track length} &= 16,700 - (27 \times 5 \times 1.5) = 16,498 \text{ m (See note 1 at foot.)} \\
 \text{area damaged by access tracks} &= 16,498 \times 25 = 412,438 \text{ m}^2 \\
 &\quad (25 = \text{damage} + \text{ditch} + \text{track} + \text{ditch} + \text{damage}) \\
 \text{area damaged by turbine bases} &= 27 \times (5 + 20 + 5)^2 = 24,300 \text{ m}^2 \\
 \text{area damaged by hard standings} &= 50 \times 20 \times 27 = 27,000 \text{ m}^2 \\
 \text{area damaged by borrow pits} &= 0 \text{ m}^2 \text{ (off-site quarries proposed for Whinash)} \\
 \text{thus, total area lost} &= 412,438 + 24,300 + 27,000 + 0 = 463,738 \text{ m}^2 \\
 \text{lost annual sequestration} &= 463,738 \times 19\text{gm/m}^2/\text{year} = 8.81 \text{ tonnes carbon} \\
 \text{lost site lifetime sequestration} &= 8.81 \times 25 \text{ years} = 220 \text{ tonnes carbon} \\
 \text{thus, fixation lost} &= 220 \times 44/12 = \underline{808} \text{ tonnes CO}_2
 \end{aligned}$$

**CO<sub>2</sub> emitted by peat oxidising over time**

$$\begin{aligned}
 \text{Weighted track length} &= (16,700 - (27 \times 50 \times 1.5)) = 14,675 \text{ m (See note 1 at foot.)} \\
 \text{Peat damaged by access track construction:} & \\
 &= (14,675 \times (50 + 15 + 50)) \times 0.5 = 843,813 \text{ m}^3 \\
 \text{Peat damaged by turbine base construction:} & \\
 &= (50 + 20 + 50)^2 \times 0.5 \times 27 = 194,400 \text{ m}^3 \\
 \text{Peat damaged by quarrying 'borrow' pits:} & \\
 &= 0 \text{ m}^3 \text{ (off-site quarries proposed for Whinash)} \\
 \text{Total volume of damaged peat} &= 843,813 + 194,400 + 0 = 1,038,213 \text{ m}^3. \\
 \text{Thus, CO}_2 \text{ emitted} &= 1,038,213 \times 55\text{kg C/m}^3 \times 44/12 = \underline{209,563} \text{ tonnes}
 \end{aligned}$$

**Total site CO<sub>2</sub> cost**

$$\begin{aligned}
 \text{emitted by deforestation} &= 0 \\
 \text{emitted by turbine fabrication} &= 80,258 \\
 \text{emitted by concrete manufacture} &= 6,696 \\
 \text{emitted by aggregate extraction} &= 13,750 \\
 \text{lost due to fixation loss} &= 808 \\
 \text{emitted by peat oxidation} &= \underline{209,563} \\
 \text{total emissions} &= \underline{311,075} \text{ tonnes}
 \end{aligned}$$

**What is the payback time?**

$$\begin{aligned}
 \text{Payback time} &= 311,075 \div 88,900 \text{ tCO}_2 \text{ displaced/year} \\
 &= \underline{3.5 \text{ years}}
 \end{aligned}$$

**Notes:**

- 1 The areas damaged by access tracks overlap with the areas damaged by turbine base excavations. To allow for this, the length of access track is reduced (weighted) in this calculation. The procedure used is outlined in Appendix 2. No peripheral degradation is allowed for around hard standings.
- 2 This calculation may differ slightly from the spreadsheet as the latter allows for displacement losses.

## Appendix 1

### The CO<sub>2</sub> debt due to deforestation

Some wind farms are constructed on Forestry Commission land and other plantations where it is necessary to clear fell areas of forest to avoid wind turbulence. As trees 'fix' carbon dioxide from the atmosphere, this felling also leads to a CO<sub>2</sub> debt.

Developers may agree to replant areas of forest lost to a wind farm. Over time, these may offset the original loss but not for many years, depending on the growth rate and species of tree involved. In any case, replanting can involve the ploughing of peat which would involve further CO<sub>2</sub> loss.

Because of these variables, deforestation is not calculated by the spreadsheet but, where relevant, the CO<sub>2</sub> debt due to deforestation may be worth including in the total.

#### Method

The details here are based on those in the ES for the Lochluichart Wind Farm (November 2005). The rate of carbon loss is dependent on the type of tree, its age at felling and how quickly any stored carbon is returned to the atmosphere. Table 1 below indicates the rate at which carbon is sequestered for a range of tree species with differing growth rates.

**Table 1: Carbon uptake by different woodland trees**

	Poplar	Sitka Spruce	Beech
<b>Growth Speed</b>	<b>Fast</b>	<b>Medium</b>	<b>Slow</b>
<b>Carbon sequestered (tonnes/hectare/year)</b>	<b>7.3</b>	<b>3.6</b>	<b>2.4</b>
<b>Crop rotation (years)</b>	<b>26</b>	<b>55</b>	<b>92</b>
<b>Carbon sequestered per rotation cycle (tonnes/hectare)</b>	<b>190</b>	<b>198</b>	<b>221</b>

The Lochluichart ES assumes that ten per cent of the trees on the site would be felled (30 hectares) and says that the woodland is 'native woodland' with a carbon uptake rate of 2.4t/ha/yr and a crop rotation of 92 years. This is equivalent to 221 tonnes carbon/hectare over the life cycle of the plantation.

On this basis, the loss of trees would be the equivalent to:

$$221 \times 30 \text{ ha} = 6,630 \text{ tonnes carbon}$$

$$6,630 \times 44/12 = \underline{24,310} \text{ tonnes CO}_2$$

This can be added to the total CO<sub>2</sub> debt of the wind farm – see page 7 or the spreadsheet (*Site*, cell J18, visible on screen only).



## Appendix 2

### The assumptions underlying the calculation

Construction of any power station has an energy, and thus a CO<sub>2</sub>, 'cost'. At least two industry publications have addressed the issue for wind power though both (rightly) stress the imprecise nature of any calculations due to the many assumptions made.<sup>4</sup>

#### CO<sub>2</sub> emissions during fabrication and transportation

Milborrow (1998) concluded that '... the energy payback for wind almost invariably lies in the range between 3 and 10 months'.<sup>5</sup> His study appears to address only the fabrication and construction phases: it does not refer (at least explicitly) either to transportation emissions or to base and track construction. It concludes that the manufacture of a 600 kW turbine consumes 830 MWh of electricity. This figure is used here. Since turbine manufacture involves very large steel castings and is energy intensive, it is considered that economies of scale are not significant and that linear extrapolation is justified. It is, therefore, assumed that the manufacture of one MW of wind-turbine capacity consumes 1,383 MWh of electricity.

The CO<sub>2</sub> emissions arising from electricity generation depend on the fuel used: nuclear power has almost zero emissions, coal firing is usually taken as 0.86 tCO<sub>2</sub>/MWh and gas as about 0.3 tCO<sub>2</sub>/MWh. The generally accepted grid average is 0.43 tCO<sub>2</sub>/MWh and this value is used here. To allow for the CO<sub>2</sub> debt arising from transportation, it is weighted by a user-decided percentage. A default of 100 per cent is assumed in the worked example but it can be varied in the spreadsheet. Thus, it is assumed as the default that the manufacture of one MW of wind-turbine capacity emits  $(1,383 \times 0.43 \times 2) = 1,189$  tonnes of CO<sub>2</sub>. (The effect of transportation on the final payback is small.)

#### CO<sub>2</sub> emissions during erection

The base of a 100-metre high turbine is typically 15 or 16 metres square by 1.5 metres deep and the concrete used in its manufacture weighs 2.4 tonnes/m<sup>3</sup>. Hence, the base weight is  $15 \times 15 \times 1.5 \times 2.4 = 810$  tonnes. The collar to which the tower is fixed typically adds 50 tonnes and, allowing for concrete in the load-bearing stands, the total is around 1,000 tonnes per turbine. About 32 tonnes of reinforcing steel are used. Estimates of emissions from concrete range from 0.36 to 1.25 tCO<sub>2</sub>/tonne cement: 0.8 tonnes is assumed here.<sup>6</sup> The cement content of concrete varies but a reasonable assumption is 12 per cent by weight or 120 tonnes per base. The other constituents are sand (35%), crushed stone (45%) and water. The CO<sub>2</sub> debt arising from their quarrying and transportation is taken to be about 0.1 tCO<sub>2</sub>/tonne. Steel manufacture releases about 2 tCO<sub>2</sub>/tonne.<sup>7</sup> Thus, construction of the concrete base for a typical modern wind turbine is assumed to emit:

Cement manufacture	=	120 tonnes x 0.8 tCO <sub>2</sub> /tonne	=	96 tonnes
Steel manufacture	=	32 tonnes x 2.0 tCO <sub>2</sub> /tonne	=	64 tonnes
Sand and aggregate extraction	=	880 tonnes x 0.1 tCO <sub>2</sub> /tonne	=	88 tonnes
			Total:	= 248 tonnes CO <sub>2</sub>

#### CO<sub>2</sub> emissions due to access track construction and base ballast

Access tracks are made from crushed rock and are typically five metres wide and at least 0.5 metres

<sup>4</sup> Krohn, S (Ed: for the Danish Wind Turbine Mfgs Assn.) *The energy balance of modern wind turbines*. Windpower Note, Dec 1997. Milborrow D (1998), *Dispelling the myths of energy payback time*, WindStats Newsletter, Vol. 11 (2).

<sup>5</sup> Figure 4 in Milborrow's paper shows a range from three to 30 months. The discrepancy is not explained.

<sup>6</sup> See e.g. [www.wbcds.org](http://www.wbcds.org); [www.ieagreen.org.uk](http://www.ieagreen.org.uk) or [www.p2pays.org/ref/10/09944.htm](http://www.p2pays.org/ref/10/09944.htm).

<sup>7</sup> See, e.g., [www.azom.com/news.asp?newsID=2530](http://www.azom.com/news.asp?newsID=2530).

deep. A nominal half-kilometre of access track for each turbine thus requires  $500 \times 5 \times 0.5 = 1,250 \text{ m}^3$  of crushed rock. A turbine base is weighed down by about 1,000 tonnes ( $500 \text{ m}^3$ ) of aggregate and a hard standing area of about  $50 \times 20 \times 0.5 \text{ m}^3$  is normally required per turbine to accommodate cranes and other vehicles. A value for the density of aggregate of two tonnes/ $\text{m}^3$  and a  $\text{CO}_2$  cost of 0.1 tonnes/tonne are assumed. These activities typically emit  $350 \text{ tCO}_2/\text{turbine}$  but they are site-dependent parameters and data from the ES should be used.

### **$\text{CO}_2$ emissions due to lost sequestration by Sphagnum mosses**

The uptake of  $\text{CO}_2$  varies from bog to bog and is influenced by several factors including mean annual temperatures, rainfall, altitude, latitude and proximity to the sea. It will be highest in 'active' bogs where a near-complete coverage of growing bog moss is contributing new peat. A recent study estimated the long-term carbon accumulation rate in growing peatlands to be in the region of  $29 \text{ gms carbon/m}^2/\text{year}$ .<sup>8</sup> Many UK bogs are drier today than in the past due to human draining activity or over-grazing and may have lower growth rates: a figure of  $19\text{g/m}^2/\text{yr}$  is used here.

### **$\text{CO}_2$ emissions due to the oxidation of stored peat**

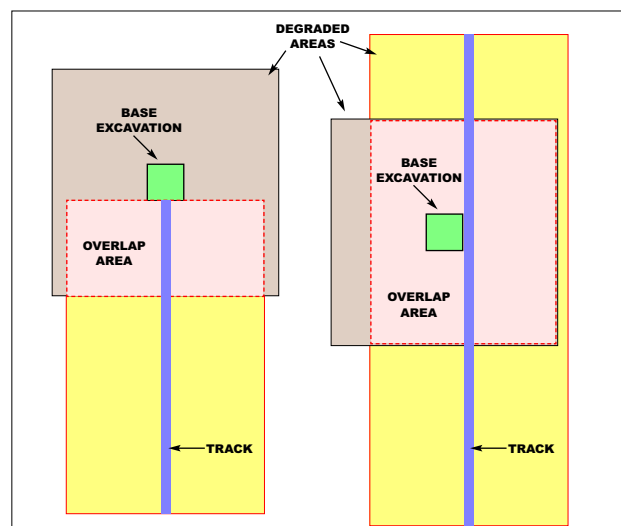
The figure used here for carbon loss from oxidising peat was recently calculated by Scottish Natural Heritage as follows:<sup>9</sup>

- Moisture content of peat = 90-93% – so assume 90%, i.e. 10% dry matter
- Carbon content of dry peat = 49 to 62% – so assume 55%
- Carbon content of *in situ* peat =  $55 \times 10 = 5.5\%$
- Thus, carbon content/ $\text{m}^3$  =  $55\text{kg}$  (assuming peat to weigh  $1 \text{ t/m}^3$ )

### **Weighting the length of the access tracks**

Since access tracks pass adjacent to or terminate at turbine bases, there is an overlap of the damaged areas around them. Calculation of the degraded area on a site must allow for this.

It is done here by reducing the nominal length of the access tracks. The graphic shows a 20-metre base with a 50-metre degradation zone and a 5-mmetre access track (also with a 50 metre degradation zone but without ditches), terminating at (left) and passing beyond (right) the accessed excavation edge. On the left, the overlap is equivalent to shortening the access track by the degradation extent and, on the right, to roughly twice the degradation extent.



A reasonable weighting is obtained by shortening the total length of track by 1.5 times the degradation extent once for every turbine. (The ratio can be adjusted in the spreadsheet in Sums, cell B12.) The weighted length is given by:

Total length of track - (no of turbines x extent of degradation [i.e. 5, 50 or 100 metres] x 1.5).

For the worked example:  $16,700 - (27 \times 50 \times 1.5) = 14,498$  metres.

- If the access track is around 500 metres per turbine, it is sufficient to shorten it by about two per cent for the low scenario, 15 per cent for the medium and 30 per cent for the high.

<sup>8</sup> Gorham E (1991). *Northern peatlands: role in the carbon cycle and probable responses to climate warming*. Ecology Applications, Vol. 1, pp182-195.

<sup>9</sup> Scottish Natural Heritage Technical Guidance Note, *Windfarms and Carbon Savings*, June 2003.

### Appendix 3

#### Using a spreadsheet to automate the calculation

A spreadsheet that calculates the payback time for wind farms sited on peatlands using the method and assumptions described in this paper has been written by the Scottish Wind Assessment Project (SWAP). It can be obtained by sending an e-mail to [press@ref.org.uk](mailto:press@ref.org.uk). Below are some notes for users.

Values for the site in question should be found in the Environmental Statement (including a figure for mean peat depth) although independent verification is advised where possible.

- 1 The spreadsheet was written using Microsoft Excel 2000 but should run with later versions. It is suggested that you work with a copy of the original file.
- 2 There are two worksheets: *Site* and *Sums*. If the information is entered into the yellow-shaded cells on the *Site* worksheet, payback time for each scenario is shown at the foot.
- 3 There are default values for some variables: 248 tCO<sub>2</sub> for the debt per turbine base, 500 x 5 x 0.5 m<sup>3</sup>/turbine for access tracks, 1,000 tonnes (500 m<sup>3</sup>)/turbine for ballast, 30% for load factor and 0.43 tCO<sub>2</sub>/MWh for fuel displacement. These are used if the appropriate cells are left blank but are over-ruled if values are entered. This allows a quick comparison of the figures in the ES against typical values – the two should be roughly the same. If not, the discrepancy may merit investigation.

The aggregate requirement reported in the ES can be entered into cell F11. A value is also calculated from the figures for the access tracks, hard standings and ballast (cell F12) and from the defaults (cell F13). These should be roughly the same. If they are not, the discrepancy may merit investigation. The formula examines F11 if present, then F12 if present, then F13.

- 4 If the CO<sub>2</sub> cost of deforestation (Appendix 1) is calculated and the result entered into J18, it will be included in the calculation of payback time. If not, leave the cell blank.
- 5 Assumptions (shaded brown) and intermediate results can be viewed on the *Sums* worksheet but cannot be changed: the spreadsheet is designed to perform the calculations outlined in this paper, not the (quite valid) examination of alternative hypotheses. To discuss any of the assumptions or calculations, please contact REF.
- 6 The spreadsheet is offered in good faith to inform public debate but neither SWAP nor the author can be held responsible for any use to which data derived from it are put.

The spreadsheet includes a variable called 'Displacement Efficiency'. This reflects the fact that when a wind turbine displaces generation from a conventional power station, it cannot do so at 100 per cent efficiency (even if it is invariably implied that it does).

It is true that a megawatt hour generated by a wind turbine displaces a megawatt hour generated at a coal- or gas-fired power station. If it didn't, system frequency would rise and the grid would become unstable but it is *not* true that such displacement will ever be 100 per cent efficient.

- For remote sites, average transmission losses can be as much as ten per cent of the power generated although sites closer to demand centres will have lower losses.
- The efficiency of a conventional turbine falls as its output is lowered: at its minimum possible loading of around a quarter of full load, its efficiency is typically perhaps about 65% of efficiency at full load, i.e. it uses more fuel per generated MWh at low loads than at full loads.
- A power station uses at least five per cent of its output to control itself.

Engineers from the power supply industry suggest that a value of 90 per cent for Displacement Efficiency is a reasonable and conservative assumption for most applications.

### **About the author: Dr Mike Hall, FRSC, FIBiol**

After graduating in physics and biological sciences, Dr Hall followed a career in organic chemistry and medical research as a lecturer at Swansea University (now part of the University of Wales) and, later, in the pharmaceutical industry. He has published over 100 papers.

His contributions to chemistry and biology were recognised by his election as a Fellow of the Royal Society of Chemistry and a Fellow of the Institute of Biology.

On moving to Cumbria in 1988, he became involved in many aspects of conservation and is a member of the Cumbria Wildlife Trust's Conservation Committee. He manages an SSSI for CWT which combines unusual features of both raised and valley mires, providing direct experience of peat bogs.

The pressure for wind farms in Cumbria rekindled an interest in energy matters which combined readily with his biological interests and led directly to the preparation of this paper.

### **About the Renewable Energy Foundation**

The Renewable Energy Foundation (REF) is a registered charity which aims to raise public awareness of the issues surrounding renewable energy and to encourage the creation of a structured energy policy for the United Kingdom which is both ecologically sensitive and effective. We recognise that global circumstances make it increasingly difficult for the government to create favourable conditions to facilitate market provision of clean, secure and economically priced energy with adequate and diversely sourced supplies. By contributing a diversity of technologies to an overall portfolio that is itself balanced, renewable energy could have an important part to play in ensuring that the United Kingdom is buffered as far as is possible against future crises.

The foundation wishes to ensure that our national energy debate leads to a diverse application of renewables within a balanced system of energy provision.

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