Chapter 6: Climate Change and Atmospheric Emissions

Appendix 6.1 Carbon Calculator Sensitivity Analysis and Calculation

Appendix 6.1 Carbon Calculator Sensitivity Analysis and Calculation

Appendix 6.1 Carbon Savings Model

Introduction

6.1.1 This is a Technical Appendix to Chapter 6: Climate Change and Atmospheric Emissions of the Environmental Statement (ES) for the proposed West Benhar Farm and should be read with reference to this chapter.

6.1.2 This appendix presents the assessment of the net carbon or carbon dioxide (CO_2) savings the wind farm is estimated to achieve during its lifetime. The production of electricity from wind energy leads to a reduction in CO_2 atmospheric emissions compared with coal and gas fired power stations. At the other hand, the wind farm has its own carbon "footprint" associated with the manufacturing, construction and transport of all infrastructure. Additionally, the removal of forest and peat bog leads to one-off losses of stored carbon and ongoing reductions in carbon sequestration at these locations.

6.1.3 All the above effects are quantified in this assessment and the total net carbon dioxide equivalent (CO_2e) emission savings are presented. The net savings are also expressed in terms of a "payback" period or break-even point in time. Typically, the payback period for wind farms is between 1 and 5 years compared with an overall lifetime of 25 years.

Methodology

6.1.4 The assessment of the net carbon savings follows guidance and methodologies published by the Government (Scottish Government 2011; Smith et al. 2011; Nayak et al. 2010). This methodology includes a detailed accounting of all expected losses and savings of carbon during the construction and operation of the wind farm. As part of the guidance the Government developed a spreadsheet implementation of the methodology, which is mandatory and must not be modified. Here version 2.7.0 of the spreadsheet model, published on 27 October 2012, was used and was the latest version available during this study.

6.1.5 Key model parameters and their justification are presented in the following section. Data sources range from site-specific, measured data to regional and national published datasets. Where uncertainty exists, a range has been used as a parameter value based on an estimated minimum, maximum and expectation value. The resulting net CO_2e savings and the payback period are therefore also expressed as ranges of values.

6.1.6 The assessment was undertaken for the proposed turbine model with a maximum output of 3.4 MW at an estimated load factor of 27.8%.

6.1.7 A sensitivity analysis was also undertaken whereby each input parameter was changed from its expectation value to the maximum value or the minimum value, whichever resulted in a longer payback period. This analysis therefore demonstrates the maximum uncertainty in the payback period due to the uncertainty in any particular parameter.

6.1.8 Input and (summary) result sheets are reproduced in this appendix. An electronic copy of the full model can also provided to the planning authority for review on request.

Model Input Parameters

Parameter	Expected value	Minimum possible value	Maximum possible value	Justification and comments[1]	Payback period sensitivity (months increase)[2]
Windfarm Characteristics					
Capacity factor / percentage efficiency (%)	27.8	22.8	32.8	Based on 3 months of wind data from on-site met mast. Estimated range of ±5% used. 1998–2004 average for Scotland is 30 %.	4.8
Extra capacity required for backup (%)	5	0	5	5% to be adopted if more than 20% of energy supplied is from wind.	0.0
Characteristics of peatland before windfarm development					
Average air temperature at site (°C)	9.55	6.2	12.9	1981–2010 average data from MetOffice station at Paisley. Ranges based on average daily minimum and daily maximum temperatures at the station. The sensitivity analysis suggest that the carbon payback period is not sensitive to changes in the average air temperature. Therefore no futher efforts have been made to obtain site-specific temperature data.	0.0
Carbon content of dry peat (%-weight)	56	15	65	Based on area-specific data taken from Soil Indicators For Scottish Soils (SIFFS) website (Macaulay Land Use Research Institute 2010). Data for soil unit 450, blanket peat suggests a mean carbon content estimate of 56% with a a range of 15%–65%.	1.2
Average extent of drainage around drainage features at site (m)	10	5	25	Range estimated from walkover inspection	6.5
Average water table depth at site (m)	0.10	0.00	0.30	Range estimated from walkover surveys and peat probing/coring.	0.0
Dry soil bulk density (g cm^{-3})	0.20	0.20	0.45	The dry soil bulk density of peat can vary significantly between peat bogs. The carbon balance model report (Smith et al. 2011) states that data from the National Soil Inventory of Scotland suggests an average value of 0.2 g/cm^3. The carbon balance model report also references an older source (Dryburgh 1978) quoting a range of between 0.25 g/cm^3 and 0.45 g/cm^3. Other more recent publications suggest typical dry bulk soil density values of between 0.1 g/cm^3 and 0.2 g/cm^3 (e.g. Chambers, Beilman, and Yu 2011). Here a conservatively high range of between 0.20 g/cm^3 and 0.45 g/cm^3 with an expected value of 0.20 g/cm^3 has been used based on the model guidance.	9.6

Parameter	Expected value	Minimum possible value	Maximum possible value	Justification and comments[1]	Payback period sensitivity (months increase)[2]
Characteristics of bog plants					
Time required for regeneration of bog plants after restoration (years)	5	3	7	Based on advice from RPS peat bog ecologists, it is considered that due to the drained nature of the existing peat bog vegetation could re-grow more easily and quickly compared with pristine blanket bogs. Based on this information and experience, we have therefore estimated time required for regeneration of bog plants as 5 years (3 years–7 years).	0.0
Carbon accumulation due to C fixation by bog plants in undrained peat (tC ha^{-1} yr^{-1})	0.10	0.05	0.15	SNH guidance states a value of 0.25 tC/ha/year with a range 0.12 tC/ha/year to 0.31 tC/ha/year based on literature data (Botch et al. 1995; Turunen et al. 2001). As the peat bog at the wind farm site is extensively drained, the expected value has been estimated as 0.10 tC/ha/year (0.05 tC/ha/year – 0.15 tC/ha/year). This estimate is based on professional judgement and published carbon accumulation rates. This recognises that carbon accumulation at the site may be slightly below published data for typical peat bogs.	0.0
Forestry Plantation Characteristics					
Area of forestry plantation to be felled (ha)	13.56	13.56	13.56	Total area of forest calculated to be felled by keyholing methods for the turbines (excluding existing openspace/roads – 13.56ha), new access roads (0.91ha), upgrade of existing tracks (0.34ha) and other infrastructure not in the turbine keyholes (e.g. i.e. control compound, construction compound and metmast – 0.42ha) for the construction/operaton of the windfarm as taken from Technical Appendix 4.3, Forestry Impact Analysis.	N/A
Average rate of carbon sequestration in timber (tC ha^{-1} yr^{-1})	3.60	3.15	3.60	Based on SNH guidance. Lower estimate is by Forestry Commission.	0.0
Counterfactual Emmision Factors					
Coal-fired plant emission factor (tCO_2/MWh)	0.912	0.912	0.912	CO_2 emission factors for electricity production from coal, fossil fuels and the current mix of energy sources across the UK ("grid mix") have been updated using the most recently published data by DECC (2012, p. 124). These data are for 2011.	N/A
Grid mix emission factor (tCO_2/MWh)	0.443	0.443	0.443		N/A
Fossil fuels mix emission factor (tCO_2/MWh)	0.609	0.609	0.609		N/A

Parameter	Expected value	Minimum possible value	Maximum possible value	Justification and comments[1]	Payback period sensitivity (months increase)[2]
Foundation and hardstanding area associated with each turbine					
Average length and width of turbine foundations (m)	13.2	13.2	18.6	Actual turbine foundations are circular with a likely 15 m diameter but if a different turbine model is selected this could be a maximum of 21m. Here a rectangular shape has been populated with an equal surface area.	1.2
Average depth of peat removed from turbine foundations (m)	3.03	2.00	4.1	Detailed peat depth surveys were undertaken during various stages of the design and environmental impact assessment process. Peat depths were estimated using peat probing, initially at a 200 m grid spacing and subsequently at a 100 m distance interval or closer near the turbine foundations, hard standing areas and access tracks. The surveyed peat depth locations were subsequently interpolated across the entire site using an Inverse Distance Weighting (IDW) method within a Geographic Information System (GIS). These interpolated peat depths were then interrogated for the distinct infrastructure elements (turbine foundations, hard standings and tracks) assessed in the carbon balance model. For the turbines which are piled (likely Turbines 2, 5 and 7) approximately 2m of peat will be removed with the others being excavated to the base of the peat with the depths based on peat probe locations as detailed in the Project Description. This results in an average peat depth to be removed of 3.03m, a minimum of 2m in piled foundations and a maximum of 4.1m.	1.2
Average depth of peat removed from hard-standing (m)	0.5	0.5	0.5	As above. Hardstandings are located adjacent to turbine foundation in areas of similar peat depth, however it is assumed that in most areas the removal of 0.5m of peat to allow construction of geotextile/crushed rock hardstanding will be appropriate subject to detailed geotechnical analysis. In some instances piled foundations may be needed for areas of deeper peat such that it is not expected that more than 0.5m of peat would require removal.	N/A
Access Tracks					
Floating road depth (m)	0.5	0.2	0.7	Typical values for road construction thickness/settlement	1.2
Length of floating road that is drained (m)	4000	4000	4000	Full length of the road is drained by use of permeable construction	N/A

Parameter	Expected value	Minimum possible value	Maximum possible value	Justification and comments[1]	Payback period sensitivity (months increase)[2]
Average depth of drains associated with floating roads (m)	0.5	0.2	0.7	Typical values given the construction proposed	1.2
Average depth of peat for excavated road (m)	1.25	0.5	2	There are small sections of proposed cut/excavated tracks in the area of Turbine 1 and south of Turbine 2 and peat depths in these areas range from 0.5m to 2m so an average of this has been used given the small length of these sections.	1.2
Additional Peat excavated (not already accounted for above)					
Volume of additional excavated peat (m^3)	2113	2113	2113	This has been used to account for peat affected by the construction of the control building compound (25m x 12m = 300m^2), construction compound (50m x 50m = 2500m^2) and permanent met mast area (95m x 15m = 1425m^2). Volume assumes 0.5m removed at each location.	N/A
Area of additional excavated peat (m^2)	4225	4225	4225		N/A
Improvement of C sequestration at site by blocking drains, restoration of habitat etc					
Area of felled plantation to be improved (ha)	6.7	6.7	6.7	It is proposed that an area of approximaltey 6.7 ha within Balbackie Plantation will be cleared of conifer plantation around Turbine 5 as part of the ongoing forestry works on site in 2016. This area will not be replanted for forestry and instread will be restored as bog habitat to mitigate against the loss of Annex 1 habitats due to the construction of the wind farm.	N/A
Water table depth in felled area before improvement (m)	0.3	0.1	0.5	These estimates are based on practical experience gained from direct involvement and monitoring (vegetation and hydrology) of restoration on similar sites (e.g. Blacklaw WF, Clyde WF, Whitelee WF) by RPS ecologists specialising in peat bogs and peat restoration. This estimate takes into consideration altitude, exposure, site wetness, existing vegetation and new techniques for increasing the rate of recolognisation (e.g. sphagnum beads).	0
Water table depth in felled area after improvement (m)	0.1	0	0.2		0
Time required for hydrology and habitat of felled plantation to return to its previous state on improvement (years)	5	3	7		0
All other model parameters not detailed above				All other model parameter values are directly taken from the proposed wind farm infrastructure and includes various dimensions, volumes, etc.	N/A

Parameter	Expected value	Minimum possible value	Maximum possible value	Justification and comments[1]	Payback period sensitivity (months increase)[2]

Notes:

1. Where applicable values have been chosen taking into account guidance accompanying the model (Scottish Government 2011; Smith et al. 2011).

2. The carbon payback time sensitivity has been calculated by changing the parameter's expected value to the maximum and minimum possible value and noting the maximum increase to the payback time. This sensitivity test indicates how much greater the payback time could be based on the (site-specific) uncertainty in the particular parameter. Changing all parameters to the maximum possible value (or minimum, whichever results in a greater payback time), results in an increase of 77 months in carbon payback time.

Spreadsheet Model Input Data Sheet

Core input data

ENTER INPUT DATA HERE! VALUES SHOULD ONLY BE CHANGED ON THIS SHEET. **DO NOT USE EXAMPLE VALUES AS DEFAULTS!** ENTER YOUR OWN VALUES THAT ARE SPECIFIC TO YOUR PARTICULAR SITE.

Note: The input parameters include some variables that can be specified by default values, but others that must be site specific. Variables that can be taken from defaults are marked with purple tags on left hand side.

Click here to move to Payback Time

Click here to return to Instructions

Input data	Expected values: Enter expected value here	Record source of data	Possible range of values: Enter minimum value here	Record source of data	Enter maximum value here	Record source of data
Windfarm characteristics						
Dimensions						
No. of turbines	8		8		8	
Lifetime of windfarm (years)	25	Fixed	25		25	
Performance						
Power rating of turbines (turbine capacity) (MW)	3.4		3.4		3.4	
Capacity factor	Direct input of capacity factor		Direct input of capacity factor		Direct input of capacity factor	
Enter estimated capacity factor (percentage efficiency)	27.8		22.8		32.8	
Backup						
Extra capacity required for backup (%)	5		0		5	
Additional emissions due to reduced thermal efficiency of the reserve generation (%)	10		10		10	
Carbon dioxide emissions from turbine life - (eg. manufacture, construction, decommissioning)	Calculate wrt installed capacity		Calculate wrt installed capacity		Calculate wrt installed capacity	
Characteristics of peatland before windfarm development						
Type of peatland	Acid bog		Acid bog		Acid bog	
Average annual air temperature at site (^oC)	9.55		6.2		12.9	
C Content of dry peat (% by weight)	56		15		65	
Average extent of drainage around drainage features at site (m)	10.00		5.00		25.00	
Average water table depth at site (m)	0.10		0.00		0.30	
Dry soil bulk density (g cm^{-3})	0.20		0.20		0.45	
Characteristics of bog plants						
Time required for regeneration of bog plants after restoration (years)	5		3		7	
Carbon accumulation due to C fixation by bog plants in undrained peats (tC ha^{-1} yr^{-1})	0.1		0.05		0.15	
Forestry Plantation Characteristics						
Method used to calculate CO_2 loss from forest felling	Enter simple data		Enter simple data		Enter simple data	
Area of forestry plantation to be felled (ha)	15.23		15.23		15.23	
Average rate of carbon sequestration in timber (tC ha-1 yr-1)	3.60		3.15		3.60	
Counterfactual emission factors						
To update counterfactual emission factors from the web — Click here (not yet operational)						
Coal-fired plant emission factor (t CO_2 MWh^{-1})	0.912		0.912		0.912	
Grid-mix emission factor (t CO_2 MWh^{-1})	0.443		0.443		0.443	
Fossil fuel-mix emission factor (t CO_2 MWh^{-1})	0.609		0.609		0.609	
Borrow pits						
Number of borrow pits	0		0		0	
Average length of pits (m)						
Average width of pits (m)						
Average depth of peat removed from pit (m)						
Foundations and hard-standing area associated with each turbine						
Method used to calculate CO_2 loss from foundations and hard-standing	Rectangular with vertical walls		Rectangular with vertical walls		Rectangular with vertical walls	
Average length of turbine foundations (m)	13.2		13.2		18.6	
Average width of turbine foundations (m)	13.2		13.2		18.6	
Average depth of peat removed from turbine foundations (m)	3.03		2.00		4.10	
Average length of hard-standing (m)	45		45		45	
Average width of hard-standing (m)	25		25		25	
Average depth of peat removed from hard-standing (m)	0.50		0.50		0.50	
Access tracks						
Total length of access track (m)	5518		5518		5518	
Existing track length (m)	2631		2631		2631	
Length of access track that is floating road (m)	2673		2673		2673	
Floating road width (m)	5		5		5	
Floating road depth (m)	0.50		0.20		0.70	
Length of floating road that is drained (m)	2673		2673		2673	
Average depth of drains associated with floating roads (m)	0.50		0.20		0.70	
Length of access track that is excavated road (m)	214		214		214	
Excavated road width (m)	5		5		5	
Average depth of peat excavated for road (m)	1.25		0.50		2.00	
Length of access track that is rock filled road (m)	0		0		0	
Rock filled road width (m)						
Rock filled road depth (m)						
Length of rock filled road that is drained (m)						
Average depth of drains associated with rock filled roads (m)						
Cable Trenches						
Length of any cable trench on peat that does not follow access tracks and is lined with a permeable medium (eg. sand) (m)	0		0		0	
Average depth of peat cut for cable trenches (m)						
Additional peat excavated (not already accounted for above)						
Volume of additional peat excavated (m^3)	2113		2113		2113	
Area of additional peat excavated (m^2)	4225.0		4225.0		4225.0	
Peat Landslide Hazard						

Weblink: Peat Landslide Hazard and Risk Assessments: Best Practice Guide for Proposed Electricity Generation Developments			
Improvement of C sequestration at site by blocking drains, restoration of habitat etc			
Improvement of degraded bog			
Area of degraded bog to be improved (ha)			
Water table depth in degraded bog before improvement (m)			
Water table depth in degraded bog after improvement (m)			
Time required for hydrology and habitat of bog to return to its previous state on improvement (years)			
Improvement of felled plantation land			
Area of felled plantation to be improved (ha)	6.7	6.7	6.7
Water table depth in felled area before improvement (m)	0.30	0.10	0.50
Water table depth in felled area after improvement (m)	0.10	0.00	0.20
Time required for hydrology and habitat of felled plantation to return to its previous state on improvement (years)	5	3	7
Restoration of peat removed from borrow pits			
Area of borrow pits to be restored (ha)			
Water table depth in borrow pit before restoration (m)			
Water table depth in borrow pit after restoration (m)			
Time required for hydrology and habitat of borrow pit to return to its previous state on restoration (years)			
Removal of drainage from foundations and hardstanding			
Water table depth around foundations and hardstanding before restoration (m)			
Water table depth around foundations and hardstanding after restoration (m)			
Time to completion of backfilling, removal of any surface drains, and full restoration of the hydrology (years)			
Restoration of site after decomissioning			
Will the hydrology of the site be restored on decommissioning?	No	Yes	Yes
Will you attempt to block any gullies that have formed due to the windfarm?	No	Yes	Not applicab
Will you attempt to block all artificial ditches and facilitate rewetting?	Yes	Not applicab	Yes
Will the habitat of the site be restored on decommissioning?	No	Yes	Yes
Will you control grazing on degraded areas?	No	Yes	Not applicab
Will you manage areas to favour reintroduction of species	Yes	Not applicab	Yes

Choice of methodology for calculating emission factors	Site specific (required for planning applications)

Core input data

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Summary of Results

6.1.9 The total expected carbon emission savings compared with alternative electricity production methods are shown in Table 1. The total emissions or losses in stored carbon, due to the construction and operation of the wind farm are shown in Table 2.

Table 1 Estimated Carbon Emission Savings over the Wind Farm's Lifetime ($ktCO_2$)

Alternative Electricity Generation	Expected	Minimum Estimate	Maximum Estimate
Coal	1,510	1239	1782
Grid mix	734	602	866
Fossil fuels	1008	827	1190

Table 2 Estimated Carbon Losses over the Wind Farm's Lifetime ($ktCO_2e$)

Cause	Expected		Minimum Estimate	Maximum Estimate
Turbine life (manufacturing etc)	21.7	(32 %)	21.7	21.7
Backup capacity	18.1	(27 %)	0	18.1
Reduced carbon fixing potential	0.1	(<0.1 %)	<0.1	0.4
Soil Organic Matter	23.4	(34 %)	1.1	180
Loss of DOC & POC leaching	<0.1	(<0.1 %)	0.1	6.3
Forestry felling	5.0	(7 %)	4.4	5.0
Total	68.3	(100 %)	27.4	232

6.1.10 Table 2 indicates that, assuming the expected values, similar proportions of carbon is lost due to the manufacturing and construction of the turbines, required backup electricity generation capacity and losses in stored carbon in peat bogs. A smaller proportion of losses occur due to forestry felling.

6.1.11 Given that the total carbon emission savings are greater than the losses, a "payback period" or break-even point is calculated as shown in Table 3 which can be compared with the total lifetime of the wind farm of 25 years.

Table 3 Carbon Losses Payback Periods (yr)

Alternative Electricity Generation	Expected	Minimum Estimate	Maximum Estimate
Coal	1.1	0.4	4.7
Grid mix	2.3	0.7	9.6
Fossil fuels	1.7	0.5	7.0

6.1.12 Depending on which alternative electricity generation method is considered, the payback period is estimated between 1.1 and 2.3 years with an upper estimate between 4.7 and 9.6 years.

6.1.13 Currently there is no guidance available on what payback period is considered acceptable for planning purposes and whether the carbon savings over the life-time of the wind farm outweigh the losses and emissions of carbon which occur primarily during the construction phase. In this case the expected carbon losses are less than 10% of the savings compared with the current "grid-mix" electricity generation and in absence of any guidance this is considered a significantly positive effect.

Spreadsheet Model Results Sheet

Results
PAYBACK TIME AND CO_2 EMISSIONS

Note: The carbon payback time of the windfarm is calculated by comparing the loss of C from the site due to windfarm development with the carbon-savings achieved by the windfarm while displacing electricity generated from coal-fired capacity or grid-mix.

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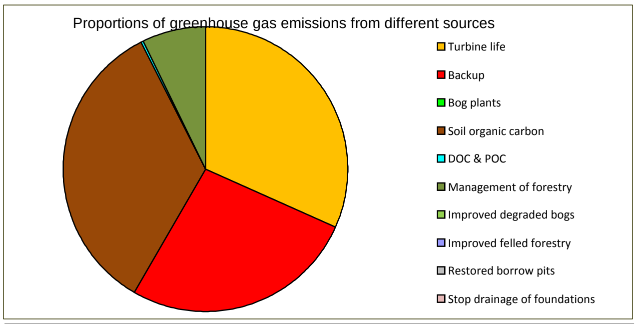
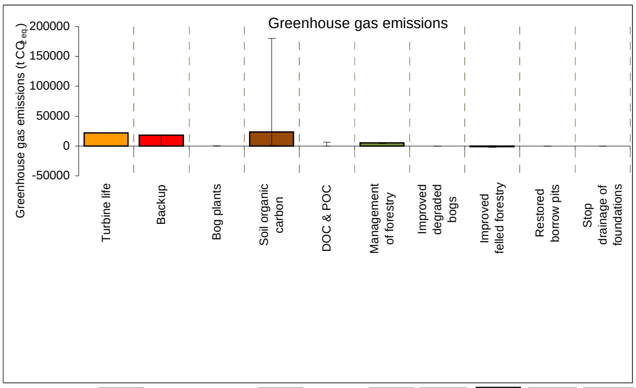
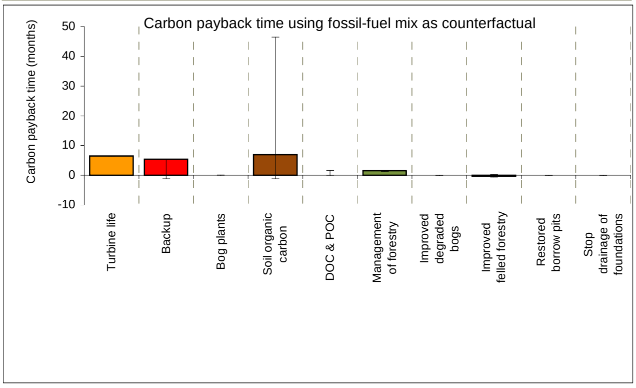
	Exp.	Min.	Max.
1. Windfarm CO_2 emission saving over…			
…coal-fired electricity generation ($tCO_2\ yr^{-1}$)	60411	49545	71276
…grid-mix of electricity generation ($tCO_2\ yr^{-1}$)	29344	24066	34622
…fossil fuel - mix of electricity generation ($tCO_2\ yr^{-1}$)	40340	33085	47595
Total CO_2 losses due to wind farm (t CO_2 eq.)			
2. Losses due to turbine life (eg. manufacture, construction, decomissioning)	21674	21674	21674
3. Losses due to backup	18138	0	18138
4. Losses due to reduced carbon fixing potential	131	41	442
5. Losses from soil organic matter	23355	1110	180036
6. Losses due to DOC & POC leaching	8	145	6283
7. Losses due to felling forestry	5026	4398	5026
Total losses of carbon dioxide	68333	27369	231599
8. Total CO_2 gains due to improvement of site (t CO_2 eq.)			
8a. Gains due to improvement of degraded bogs	0	0	0
8b. Gains due to improvement of felled forestry	-1077	380	-2189
8c. Gains due to restoration of peat from borrow pits	0	0	0
8d. Gains due to removal of drainage from foundations & hardstanding	-9	5	-100
Total gains	-1086	385	-2289

RESULTS	Exp.	Min.	Max.
Net emissions of carbon dioxide (t $CO_{2\ eq.}$)	**67247**	**25080**	**231984**
Carbon Payback Time			
…coal-fired electricity generation (years)	1.1	0.4	4.7
…grid-mix of electricity generation (years)	2.3	0.7	9.6
…fossil fuel - mix of electricity generation (years)	**1.7**	**0.5**	**7.0**







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Results
PAYBACK TIME AND CO_2 EMISSIONS
Note: The carbon payback time of the windfarm is calculated by comparing the loss of C from the site due to windfarm development with the carbon-savings achieved by the windfarm while displacing electricity generated from coal-fired capacity or grid-mix.

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