Xi Engineering Consultants

Pines Burn Windfarm - Eskdalemuir Constraints Solution

Empirical data driven approach to construct 11 turbines within MoD allocated budget whilst removing adverse impact risk to the Eskdalemuir Array

Presented to: Energiekontor

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1. Executive Summary

This document outlines the approach Energiekontor have taken in conjunction with subject matter experts Xi Engineering Consultants Ltd (Xi) to provide evidence to allow the Ministry of Defence (MoD) to remove their current objection for Pines Burn wind farm with respect to the Eskdalemuir seismic station. It should be noted that the approach taken mitigates the risk of exceeding budget as the turbines will be built out in two distinct phases allowing evidence of compliance prior to installation of the second phase.

Pines Burn was registered on the MoD Eskdalemuir spreadsheet under reference DIO 23260 in July 2016 and received no objection from the MoD regarding Eskdalemuir and received a seismic budget allowance of 0.0310826 nm. The seismic budget allocation is based on an intentionally conservative worst-case turbine algorithm produced by Xi in 2014 used by the MoD and is based on the dimensions and location of the turbines. Subsequently, Energiekontor split the site up into two phases and requested an increase in turbine size which received an objection from the MoD. The 0.336nm seismic budget is currently full, and they have no further budget to issue for the size increase based on this worst-case algorithm.

Xi have conducted substantial work packages to allow the Scottish Government and MoD, to release further budget whilst safeguarding the array by reducing the conservatism of the 2014 algorithm and reflecting the latest empirical data. As scientific understanding has increased, all data and evidence suggests that a turbine will not produce the high seismic levels assumed by the worst-case algorithm. Energiekontor engaged Xi directly to ensure that they will not adversely affect the Seismic array above that of their current allocated budget.

Empirical data shows that the installed turbines at Pines Burn will produce seismic levels less than the budget allocated by the MoD. Technical risks relating to the seismic levels of the turbines to be deployed at Pines Burn have been minimised through separating the turbine installation into two distinct Phases. This unique approach de-risks deployment and safeguards the array by gathering site specific empirical data in phase one prior to the deployment of phase 2, thereby ensuring that phase 2 will have no greater impact on the array than that allocated. The turbines included in the first Phase have been shown to be significantly under the budget allocation even when the 'worst case' algorithm is adopted. By conducting seismic measurements of operational candidate turbines and site background levels, Xi have evidenced that the candidate turbine has a seismic signature that would enable all 11 x Nordex N133 machines included in Phase 1 and Phase 2 to be deployed at Pines Burn within the allocated seismic budget of the original application. To evidence that the site will not exceed the seismic budget allocation, an operational measurement campaign will be undertaken once the Phase 1 development has been completed.

Action	Name	Date	Version	Amendment
Originator	Dr M Chung	20/01/2023	v1	Issue
Checked by	Dr M P Buckingham	25/01/2023	V2	Review
Reviewed by	R. Horton	27/01/2023	V3-5	Review & Updates
Director review	Dr MP Buckingham	31/1/2023	V4	Director review

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Contents

2. Background to Eskdalemuir

2.1. Eskdalemuir History 1962-2013

The Eskdalemuir Seismological Recording Station is located in the Scottish Borders and is a monitoring facility where seismological, magnetic and other environmental parameters are monitored.

The seismometer array at Eskdalemuir (EKA) has two arms, each of ten seismometers, and became operational on 19 May 1962. The array is operated by AWE Blacknest (AWE) and is part of the seismic network of the organisation set up to help verify compliance with the Comprehensive Test Ban Treaty (CTBT) which bans nuclear explosions.

Concerns were raised that vibrations from wind turbines might affect the ability of EKA to operate properly, and the Ministry of Defence (MoD) were advised to set a maximum permissible background vibration budget within a 50km radius of the Eskdalemuir array in order to safeguard its effectiveness in accordance with the CTBT. Beyond 50km, it was determined that the vibration contribution from a wind turbine is negligible and is not included in the vibration budget. The maximum vibration budget that was deemed to be acceptable from all wind turbines that might be built within 50km of the array was set at a threshold amplitude of 0.336nm. This budget was subsequently agreed by the Comprehensive Test Ban Treaty Organisation (CTBTO) in Vienna.

Xi were commissioned by the Eskdalemuir Working Group (EWG) in 2013 to develop a robust physics-based approach to estimating the worst-case ground vibration produced by wind turbines. Xi developed such an algorithm, which is currently used by the MoD to calculate the worst-case cumulative effect of all wind turbines on EKA; see 'Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project'. It is this experience that makes Xi uniquely qualified to assess and deliver a solution to mitigate the seismic vibration risk from wind turbines within the Eskdalemuir statutory consultation zone. The Xi algorithm requires the distance to the array, turbine diameter and the tip height to estimate the seismic vibration.

Due to the limited public data available on seismic emissions from wind turbines at the time, a conservative 'worst-case' approach was adopted. This 2014 turbine algorithm currently used by the MoD to allocate budget is effectively two turbines combined to provide a significant safety factor. The budget algorithm is designed with safety factors such that it over-predicts the output of any single turbine.

Xi's work: "Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project" was reviewed by the Ministry of Defence Subject matter experts (Dr D Bowers) who subsequently presented to the CTBTO (Comprehensive Nuclear-

Test-Ban Treaty Organization) and was ultimately accepted by the Scottish Government. Adopting the Release 2.0 of Substantial Research Project algorithm opened up over 1GW of onshore wind power within the 50km Eskdalemuir zone compared to the MoD's earlier approach.

2.2. Current Developments

The 2014 algorithm currently used by the MoD to calculate the budget (at the time of writing) takes a highly conservative approach. By design, the algorithm used includes factors of safety appropriate to the data sample size available at the time, ensuring that the algorithm over-estimates the cumulative seismic vibrations produced by wind turbines and does not compromise the seismic array.

The Eskdalemuir Working Group (EWG) was reformed in 2018 with a view to reviewing the Eskdalemuir Consultation Zone's vibration budget considering current installed developments and improvements in Wind Turbine Generator Technologies. The Eskdalemuir working group is formed of the Scottish Government, MoD, UK Government, Renewable UK and Scottish Renewables and invited industry experts. All parties are directly working with Scottish Government to resolve the barrier to development in the area.

Xi Engineering Consultants, as subject matter experts in this area, have been engaged by both the Scottish Government (SG) and the EWG to audit the turbines within the region to obtain actual seismic measurement data from the wind farms within the Eskdalemuir consultation zone. A series of phased work packages (Phases 1 through 5) were carried out, which culminated in a measurement campaign of several sites within the region and the delivery of the report 'SGV_204_Tech_Report _v12 Field audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions' in February 2022 and 'SGV-205-LimitSet-TechReport-v11 Calculations to confirm maximum turbine seismic level to deploy minimum of 1GW deployment, in October 2022..

Directly measuring the seismic output of a greater number of turbines in the consultation zone allows the reduction of the safety factor previously applied in the 2014 algorithm. This reduction ultimately allows further wind capacity to be deployed within the region without breaching the 0.336nm absolute seismic budget within the consultation zone.

All wind turbines measured in appropriate geology to date by Xi produce less vibration than the conservative 'worst-case' turbine budget algorithm. Xi have been conducting additional studies for the Scottish Government to show how much additional capacity could be delivered in the region if modern turbines were used (XIEnegineering, 2020) (XIEngineering, Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning, 2020). Whilst extremely dependant on distance to the array, calculations show a minimum of 1GW of additional development could be freed up.

A further desk-based study (Phase 5) has been completed for the Scottish Government following on from the Phase 4 report and reflecting on initial findings from the Onshore Wind Policy Statement (OnWPS) consultation responses. The main aim of this study was to provide the Scottish Government with evidence to help quantify and consider how much capacity could be achieved through future developments within the zone, with these developments directly contributing to SG's ambitions for onshore wind. In the draft OnWPS this ambition was outlined as 8-12 GW of additional installed capacity across Scotland.

The Scottish Government commissioned the calculation of what seismic output limit could be established if a minimum GW capacity between a range of 1-2.5 GW was to be achieved within the zone.

A Seismic Impact Limit (SIL) for any given turbine is the arrival amplitude at EKA of the groundwave generated by the given turbine (in nanometres) relative to output power (in megawatts).

Effectively the maximum seismic level a turbine could contribute to the budget for a given maximum power output. The adoption of such a limit by the Scottish Government would ensure that turbines placed closer to the array have a minimal seismic emission.

2.3. Revised Eskdalemuir Working Group EWG).

The EWG has been restructured for 2023 reducing its core membership to

- Scottish Government
- UK Government
- Ministry of Defence
- Heads of Planning Scotland (HOPS)
- Industry bodies (i.e., Scottish Renewables, RenewableUK)

This revised structures' aim is to collectively develop an approach regarding efficient deployment of onshore wind resource within the 50km Consultation Zone recognising that Ministry of Defence (MoD) must maintain safeguarding requirements for the Eskdalemuir Seismic Array.

The Scottish Government have raised the two main approaches which they intend to pursue.

Approach 1. Establishing a Seismic Impact Limit for Eskdalemuir Seismic Array and the consultation zone

In order to secure a minimum additional capacity of 1 GW within this zone and encourage the use of turbines with the lowest seismic impact, the Scottish Government would require that any proposal yet to be determined must limit the seismic impact of each individual turbine within the consultation zone to 0.00809 nm.MW-0.5*, and ensuring the 0.336nm threshold is not exceeded

*This limit is based on calculations undertaken by Xi Engineering on behalf of the Scottish Government.

Approach 2. Deployment Maximisation Zone at the Eskdalemuir Seismic Array

To aid in protection of the array, in addition to maximising potential for onshore wind deployment in areas with lesser impact on the array, we would replace the existing 10km exclusion zone with a 15 km exclusion zone. This means that no turbine could be constructed within a 15 km radius of the Eskdalemuir Seismic Array. This would apply only to applications submitted after the finalisation of such an approach.

It is acknowledged that this work is due to be delivered by Q4 2023.

With regards the Pines Burn windfarm both approaches will not affect the proposed two phased approach. The site is located some 27.75 km away from the array and would therefore be well outwith the proposed 15km exclusion zone. It would also comply with the proposed SIL requirements (see 3.5.2).

3. Energiekontor approach

3.1. Pines Burn Timeline

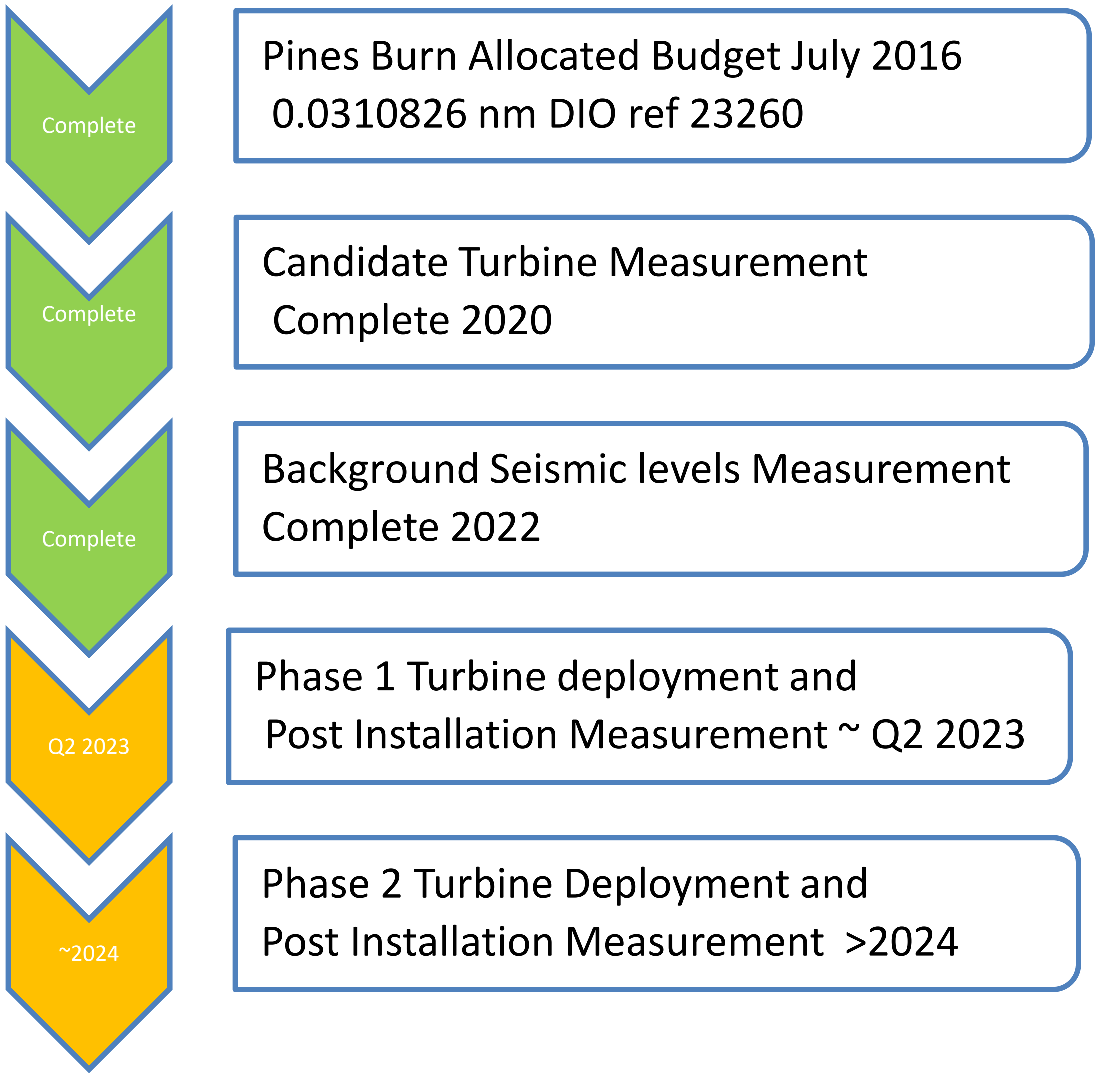

Figure 1 Process to deliver Pines Burn windfarm without exceeding allocated budget.

3.2. Pines Burn Site

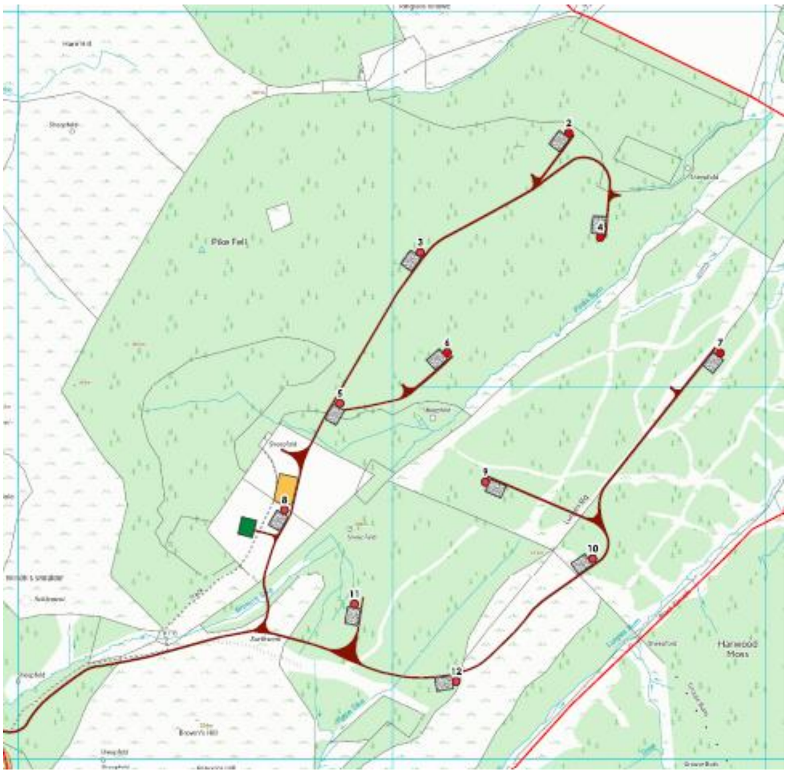

Figure 2 Site Layout of Pines Burn for Phases 1 and 2 with 11 Proposed Turbines

The proposed Pines Burn Wind Farm consists of 11 turbines with size and locations shown in Table 1. It will be built out in two phases, 7 turbines marked in black in Phase 1 and the remaining 4 turbines in Phase 2.

Xi Engineering Consultants have been working with Energiekontor to ensure that Pines Burn phases 1 and 2 can be delivered within the allocated budget of 0.0310826nm. Xi have undertaken various Desktop Studies to help Energiekontor make informed and risk averse deployment plans. As of 2017 the MoD did not object to the scheme from an Eskdalemuir Perspective and allocated budget in line with their first come first served policy. Energiekontor will provide evidence to allow the Ministry of Defence (MoD) to remove their current objection for Pines Burn wind farm with respect to the Eskdalemuir seismic station. It should be noted that the approach taken mitigates the risk of exceeding budget as the turbines will be built out in two distinct phases allowing evidence of compliance prior to installation of the second phase

Turbine No.	Easting	Northing	Distance to EKA (km)	Hub Height (m)	Rotor Diameter (m)
2	354471	606674	28.02	83.4	133
3	354074	606355	27.61	78.5	133
4	354555	606395	28.09	83.4	133
5	353859	605951	27.38	78.5	133
6	354146	606087	27.67	83.4	133
7	354876	606086	28.4	83.4	133
8	353711	605666	27.22	78.5	133
9	354248	605741	27.76	83.4	133
10	354535	605536	28.04	83.4	133
11	353898	605415	27.4	83.4	133
12	354170	605208	27.67	83.4	133

Table 1 Turbine locations and dimensions with Phase 1 in black text and Phase 2 in red. (note there are only 11 turbines as turbine No1 have been removed from planning)

Pines Burn Wind Farm has been reduced from 12 turbines to the proposed development of 11 Nordex N133 turbines at an average distance of 27.75 km from the EKA. Locations of these turbines can be seen in Table 2. During the redesign of the site the rotor diameter has been increased. Since there is currently no additional budget available from the total seismic budget of 0.336nm, when the increased rotor diameters were proposed, Energiekontor received an objection from the MoD.

It should be noted that this objection is based on the increase in turbine size submitted, as the seismic budget had been used up at that stage and as a result the MoD couldn't issue further seismic budget. It is of note that the MoD use the current methodology using the 'worst-case' turbine algorithm produced by Xi in 2014 as the basis of this objection.

To mitigate any potential budget exceedance of the proposed 11 turbines at Pines Burn according to the 'worst-case- turbine algorithm, Energiekontor have split the development into two phases: Phase 1 involving the installation of 7 turbines, while Phase 2 involves installation of a further 4 turbines. By separating the installation into two phases, it will be possible to install Phase 1 without exceeding budget based on the worst-case algorithm calculation. It will also enable Energiekontor to provide statistically robust evidence to the MoD showing that the turbines included in Phase 2 would not exceed the allocated site budget by measuring the Phase 1 turbines.

3.3. Candidate Turbine Measurements Eber Turkey

In order to get an appropriate and robust measurement of whether Pines Burn rotor variation can operate within the already allocated budget, the candidate turbine has been measured at a geologically equivalent site to that of Eskdalemuir Region.

Following Geological analysis to determine the suitability of sites, a measurement campaign of the candidate turbine was conducted. A seismic survey of Nordex N131 wind turbines with 84 m hub heights and 131 m rotor diameters was conducted at Eber Sandikli Wind Turbine Power Plant from 4th of November 2020 to the 1st of December 2020. The report of the finding is available in the document *ENE 206 Report v15 Eskdalemuir Wind Turbine Suitability Measurement.*

The Eber Sandikli Wind Turbine Site, located in Turkey is situated on pyroclastic rocks that are different to the rocks in the Eskdalemuir area. Therefore, the data was normalised to account for the difference in geology using parameters that represent damping and impedance and the resultant spectra were used to determine the number of Nordex N133 turbines that could be placed at Pines Burn. Results show that all 11 turbines could be built on the site with a high level of confidence without exceeding budget.

3.4. Pines Burn Background

In order to ensure that the seismic signature of the turbines deployed at Pines Burn are less than their allocated budget, the background seismic levels at the site must themselves be lower than the allocated budget. If local background seismic noise were greater than the budget it would be impossible to prove that the turbines do not contribute more than their allocated budget.

A background seismic measurement campaign was conducted, and the levels were quantified to be less than the budget levels and suitable for a post installation measurement campaign. The report *ENE 210 -Measurement Campaign v5 Background Measurement Campaign Pines Burn shows to site to have very low background seismic levels and* confirms the suitability of the site post installation.

3.5. Budget and Seismic Impact Limit (SIL) Estimation

3.5.1. Seismic Impact Level (SIL) methodology

Applying a Seismic Impact Limit (SIL) Policy ensures that developers placing turbines closer to the array can only deploy turbines of a lower seismic impact. The broader aim of such a policy is to maximise the potential deployment within the 50km Eskdalemuir Consultation Zone

An analogy would be that of cumulative acoustic noise; if you have a sensitive receptor in close proximity (in this case the array), and there were already a number of turbines in the vicinity, the developer would be required to ensure cumulative noise is not an issue for the receptor. This would normally be achieved by using acoustically quieter turbines. The case here seismically, is that the developer will have to ensure that each turbine placed closer to the array is seismically quiet and ultimately does not exceed a specific turbine limit for seismic vibration levels.

The seismic power produced by wind turbines has a close to linear relationship with their output power. To take account of this near linear relationship to the physical size of a turbine, the Seismic Impact Limit is specific to a turbine's maximum power output.

Definition of the SIL as documented in the Phase 5 report: *A Seismic Impact Limit for any given turbine is the arrival amplitude at EKA of the groundwave generated by the given turbine (in nanometres) relative to output power (in megawatts).*

The Seismic Impact Limit is calculated using the following equation.

$$Seismic\ Impact\ Limit = \frac{Amplitude\ at\ EKA}{\sqrt{Power}}$$

It should be noted that the SIL is calculated for each turbine independently, therefore turbines closer to the EKA will be required to be seismically quieter than those at a greater distance to the array.

The Phase 5 work produces a range of SIL limits between a minimum guaranteed 1GW additional capacity and a maximum 2.5GW additional capacity. This report assumes the 1GW minimum or 0.00809 nm.MW$^{-0.5}$ Seismic Impact Limit will be adopted.

Based on the proposed 4.8 MW turbines to be deployed at Pines Burn turbine-specific Seismic Impact Limits calculated from the Phase 5 report are 0.017724302 nm.

Were the site to adopt a machine with a higher output, the Seismic Impact Limit would change per square root of the power. Essentially the larger the machine the harder it is to meet the SIL requirements.

3.5.2. Pines Burn SIL Results

Using measured data from the Eber Sandikli Wind Turbine Power Plant in Turkey, seismic contributions were predicted based on the locations (range from the EKA) of the proposed 11 turbines at Pines Burn and the geology of the Eskdalemuir region. The calculated budget contributions for the two development phases using the 'worst-case' turbine algorithm produced by Xi in 2014 (Standard EKA) and the measured candidate turbine data from Eber can be found in Table 2.

Turbine No.	Easting	Northing	Distance to EKA (km)	Hub Height (m)	Rotor Diameter (m)	Predicted amplitude from Standard EKA model (nm)	Predicted amplitude from measured candidate data (nm)
2	354471	606674	28.02	83.4	133	0.010761305	0.008431146
3	354074	606355	27.61	78.5	133	0.011118445	0.008808257
4	354555	606395	28.09	83.4	133	0.010682175	0.008370771
5	353859	605951	27.38	78.5	133	0.011403572	0.009028084
6	354146	606087	27.67	83.4	133	0.011183044	0.008752705
7	354876	606086	28.40	83.4	133	0.010334617	0.008105423
8	353711	605666	27.22	78.5	133	0.011600675	0.009179947
9	354248	605741	27.76	83.4	133	0.01107411	0.008669684
10	354535	605536	28.04	83.4	133	0.010740821	0.008415519
11	353898	605415	27.40	83.4	133	0.011513246	0.009004209
12	354170	605208	27.67	83.4	133	0.011180275	0.008750595
					Budget used in Phase 1	0.029728631	0.02338795
					Budget used in Phase 2 (red)	0.021489051	0.016836323
					Total budget used	0.036682023	0.028817667

Table 2 Pines Burn turbine data with predicted budget contributions calculated using the Standard EKA model from 2014 and measured candidate turbine data from Eber, Turkey. Phase 1 turbines are in black, Phase 2 are in red.

Turbine No.	SIL for 4.8 MW machine 1 GW limit	Standard EKA model data SIL ratio	Measured candidate data SIL ratio
2	0.01772	1.647	2.102
3	0.01772	1.594	2.012
4	0.01772	1.659	2.117
5	0.01772	1.554	1.963
6	0.01772	1.585	2.025
7	0.01772	1.715	2.187
8	0.01772	1.528	1.931
9	0.01772	1.601	2.044
10	0.01772	1.650	2.106
11	0.01772	1.539	1.968
12	0.01772	1.585	2.025

Table 3 SIL ratios for a Scottish Government 1 GW limit using the Standard EKA model from 2014 and measured candidate turbine data from Eber, Turkey. Phase 1 turbines are in black, Phase 2 are in red. SIL ratios greater than 1 imply no mitigation would be required.

Based on the results of the background survey at Pines Burn and the Nordex N131 survey at Eber, there is high confidence the 7 Nordex N133 turbines at Pines Burn included in Phase 1 development can operate within budget. The total predicted seismic contribution for Phase 1 and Phase 2 turbines exceeds the budget allocation when using the 'worst-case' turbine algorithm produced by Xi in 2014 (i.e., Standard EKA value of 0.0367 > 0.0311 budget allocation). However, using the measured candidate turbine data from Eber, Turkey, the total predicted contribution of Phase 1 and Phase 2 is reduced to 0.0288, which is below the budget allocation. It should be expected that the measured candidate data provides a more realistic assessment of seismic contributions as opposed to the 'worst-case' approach utilised in the 2014 algorithm. Therefore, according to the measured candidate turbine data, there is high confidence that all 11 Nordex N133 turbines at Pines Burn included in Phase 1 and Phase 2 developments should be able to operate without exceeding the seismic budget allocation. Nevertheless, this will be confirmed post-Phase 1 turbine erection, through an operational site measurement campaign before the commencement of Phase 2.

The SIL ratio results shown in Table 3 highlight that the site meets the seismic requirements for both the worst-case algorithm and the measured candidate data.

Table 3 shows the SIL ratio against a Scottish Government minimum 1 GW deployment for the Standard EKA 'worst-case' model and for data from the measured candidate turbine at Eber, Turkey. A number above 1 requires no mitigation and numbers below 1 require mitigation consistent with the ratio.

4. Technical Risks and Considerations

Xi have evidenced that a measured candidate machine has a seismic signature that would mean 11 x Nordex N133 turbines could be deployed at Pines Burn Wind Farm within the allocated seismic budget of the original application.

Energiekontor have taken a unique and risk averse approach by using a 2 phased deployment approach. This deploy-measure-deploy process could be one of the methods adopted for other sites within the region, as it allows for the deployment to assist the Scottish Government in meeting it's Renewables targets while continuing to safeguard the array based on empirical evidence.

The technical risks from this project have been minimised throughout each step in the assessment process and the two phased build out process.

5. Conclusions

- Pines Burn Wind Farm has an allocated seismic budget of 0.0310826 nm allocated by the MoD based using the current intentionally conservative algorithm produced in 2014 by Xi Engineering Consultants.

- Pines Burn can build out all 11 turbines based on calculations using measured data from the candidate machine on suitable geology.

- All current scientific evidence of turbine seismic vibration levels dictates that the installed turbines at Pines Burn will produce seismic levels less than the budget allocated by the MoD.

- Measured results predict a seismic budget for all 11 turbines at 0.028817667nm, below the allocated budget.

- The background seismic levels at Pines Burn are suitably low to allow a post installation measurement.

- The two phases build out process will allow Energiekontor to demonstrate that the site will be delivered within budget, mitigating any risk of budget exceedance.

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