2 Definitions

Table 1 - Summary of acronyms used in this report relating to Seismic Impact Limit.

Acronym	Definition	Notes
SIL	Seismic Impact Limit	Constant 0.005908 nm.MW$^{-0.5}$ for 2.0 GW capacity.
PSV	Power Seismic Value	The permitted seismic impact of a turbine based on its power output. (Phase 5 - Equation 1)
TMR	Turbine Mitigation Ratio	Ratio defining if mitigation is required for a turbine. TMR < 1 requires mitigation. (Phase 5 - Equation 2). Turbine with TMR ≥1 require no mitigation and have TMR listed as "not applicable" (N/A).
MoD	Ministry of Defence	UK central government department responsible for the UK's security and interests, with jurisdiction over the protection and management of the EKA.
EKA	Eskdalemuir Seismic Array	Seismological monitoring station in the Scottish Borders which forms part of the UK's obligations under the Comprehensive Test Ban Treaty (CTBT).
ECZ	Eskdalemuir Consultation Zone	The 50 km radius protected area around the EKA, within which construction of wind farms must follow formal approval procedures with the MoD and the Scottish Government.

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3 Methodology summary

An analysis was carried out of the 21 turbines in the proposed Ravengill Energy Park (see Section 7.4 for full wind farm specifications) to determine the seismic budget requirement as well as the seismic impact based on the industry-recommended SIL deployment of 2.0 GW.

12 models were run based on Refined Phase 4 'AIFCL-101-Phase4-Rev-v13' including the Phase 4 synthetic models. These models were used to predict the seismic amplitude contributed by each turbine at Ravengill, and are explained in Appendix 7.5.1

The model for the candidate machine ATL-GSF Siemens SG 155, 155 m rotor, 122.5 m hub height, 6.6 MW type, was also used to analyse the site.

For the detailed Methodology please see Section 7.5.

4 Results

This section summarises results based on turbine specifications detailed in Table 5. Seismic budget calculations show the overall seismic noise contributions of turbines installed at Ravengill Energy Park as well as the individual turbine contributions. The SIL calculations show if all turbines could be built at while meeting the SIL for a deployment of 2.0 GW and, if not, how many turbines would require mitigation to meet the SIL.

4.1 Seismic Impact of Site (Worst-Case)

Table 2 – Calculated seismic impact level of site based on the worst-case Phase 4 model.

Model	Seismic impact level (nm)
Worst-case turbine model	***0.019135***

Table 2 shows the calculated seismic impact level of the proposed site based on scaled Phase 4 synthetic models worst case wind turbines.

4.2 Seismic Impact of Site (Candidate/Library Turbines)

Table 3 – Calculated seismic impact level of site based on chosen Candidate turbine.

Model (from Library Turbines)	Seismic impact level (nm)	Estimated seismic impact level with background noise removal (nm)
SG-155	*0.003216*	*0.002573*

Table 3 shows the estimated seismic impact level with and without background noise for the selected measured candidate turbine. Please note that the measured candidate library models are non-scalable and so results may be over- or underestimated depending on the discrepancy between candidate turbine dimensions and proposed wind farm turbine dimensions.

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4.3 SIL Conformance and Mitigation Requirements

To prevent sites close to the array from disproportionately using available Seismic Vibration Budget, the Scottish Government intends to implement a Seismic Impact Limit (SIL). The level of the SIL is still a point of debate but will likely be 0.005908 nm·MW$^{-0.5}$ for a 2.0 GW deployment for all new wind turbines installed in the ECZ.

Table 4 – Calculated seismic impact level of site based on worst-case Phase 4 model and candidate model.

	2.0 GW SIL (0.005908 nm·MW$^{-0.5}$)			2.0 GW SIL with background noise removal (0.005908 nm·MW$^{-0.5}$)		
Model	No. of Turbines requiring mitigation	Highest TMR	Lowest TMR	No. of Turbines requiring mitigation	Highest TMR	Lowest TMR
Worst-Case Model	*0*	*5.079*	*3.027*	*0*	*6.349*	*3.784*
SG-155	*0*	*29.036*	*18.362*	*0*	*36.295*	*22.953*

Table 4 shows the SIL analysis results for 2.0 GW deployment using Phase 4 synthetic models with and without background noise removal. The Power Seismic Value (PSV) is the permitted seismic impact of an individual turbine based on its power output. The Turbine Mitigation Ratio (TMR) is the seismic output of each individual turbine divided by the PSV. Indicatively, **a TMR greater than 1 signifies that the turbine will not require mitigation for the given SIL while a TMR less than 1 signifies that the turbine will likely require mitigation to meet the given SIL**.

5 Conclusions

This report asks two key questions for Ravengill:

1. What is the predicted seismic budget that will be consumed?
2. Do the turbines meet the Seismic Impact Limit?

5.1 Predicted Budget

The predicted required seismic budget using the worst-case from the Phase 4 measured turbines and assuming no background noise removal was 0.019135.

5.2 Predicted SIL requirements

Assessment against all data including the current MoD algorithm shows that the turbines at Ravengill are predicted to meet the SIL without mitigation for a 2.0 GW deployment.

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6 Reference documents

Phase 1: 'Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project'
Phase 2: 'SGV_202_Tech_Report_v07'
Phase 3: 'SGV 203 Technical report v12.pdf'
Phase4 (Refinement): 'AIFCL-101-Phase4-Rev-v1:- Field audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions'
Phase 5 (Revision): 'AIFCL-101-Phase5-Rev-v11'
Onshore wind - policy statement 2022

All publicly available documents can be downloaded here.

7 Appendix

7.1 Eskdalemuir Summary

The Eskdalemuir Seismic Array (EKA) is operated and safeguarded by the Ministry of Defence (MoD) and is used to detect ground vibration (seismic waves) caused by nuclear weapons tests. Wind turbines in the Eskdalemuir region also create seismic waves which reduce EKA's detection capabilities. To protect the detection capabilities of EKA, a 50 km consultation zone (Eskdalemuir Consultation Zone, ECZ) has been placed around the array and the cumulative impact of all wind turbines built within the zone must not exceed a seismic vibration budget of 0.336 nm. For full history of the EKA and policy updates, see Section 7.2.

Xi Engineering Consultants (Xi), as technical experts in vibration, noise, and engineering for renewables, have provided guidance to policy stakeholders in the development of new policy, as well as the supporting infrastructure and procedures for industry. This includes development of the technical algorithms utilised by the MoD, the software tool the MOD currently use for management of the ECZ, and official policy documentation for public release.

To ensure that the 0.336 nm budget is not exceeded the MoD maintained a list of operational and planned wind farms and used an algorithm based the hub height and rotor diameter of wind turbines to estimate the impact of newly proposed wind farms as they entered the planning system. The proposed site lies within the Eskdalemuir Consultation Zone and has yet to be allocated a seismic budget.

Work conducted by the Scottish Government has shown there is substantial additional budget based on moving from the 'worst case' algorithm approach to a turbine specific prediction model. The Scottish Government's draft Onshore Wind Policy Statement consultation is intended to open up additional budget and optimise the deployment within the ECZ and, to achieve this, a Seismic Impact Limit (SIL) has been proposed. The SIL is an upper limit to seismic impact on EKA that any one turbine is responsible for relative to its electrical generation capacity. Based on The Scottish Government's analysis provided by Xi Engineering Consultants, the SIL will likely be set between **0.00836 nm·MW$^{-0.5}$** and **0.00528 nm·MW$^{-0.5}$**. The industry recommended SIL is currently **0.05908 nm·MW$^{-0.5}$** for a 2.0 GW deployment, which is the figure that is assumed for the analysis in this report.

The calculation of the SIL is based on the headroom remaining were all sites in the MoD queue prior to Fawside windfarm built out in full within their budget allocation irrespective of any SIL implications. As such, the proposed wind farm has been treated in the same manner as the Scottish Government reports Phase 4 and 5, where no SIL was specified on sites prior to Fawside.

This report assumes a working understanding of considerations within the EKA. For further details, please see Section 7.2. as well as publicly available documents listed in reference Section6.

7.2 Background to Eskdalemuir

The Eskdalemuir Seismic Array is a seismological monitoring station in Dumfries and Galloway which forms part of the UK's obligations under the Comprehensive Test Ban Treaty. The array's operation can be compromised by excessive seismic noise in the vicinity, which can be produced by wind turbines operating around the array. A brief explanatory video about the global network of seismic sensors operated by the Comprehensive Test Ban Treaty Organisation (CTBTO) can be found at;

Video on Seismic Measurement by CTBTO

In May 2005, Scottish Ministers and the Ministry of Defence (MoD) issued a technical site direction with a safeguarding map to relevant planning authorities in England and Scotland as well as Scottish

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Ministers. This direction advised that any sites within 50 km of the array would require consultation with MoD before determination. This 50 km radius is often referred to as the 'consultation zone'. Within the consultation zone there is an existing hard no-build area at a radius of 10 km from the array – any applications for windfarms within 10 km will be objected to by MoD due to the unacceptable impact they would have on the array.

In 2005, a report by Styles recommended a threshold (commonly referred to as the "noise budget") of 0.336 nm of seismic noise disturbance would prevent the array's operation being comprised. Exceeding the 0.336 nm threshold would compromise the array's detection capabilities.

This was followed by the 2014 work undertaken by Xi Engineering Consultants on behalf of the Eskdalemuir Working Group, which developed a purposefully conservative algorithm and associated spreadsheet tool enabling the MoD to manage this seismic ground vibration threshold and thereby safeguard the detection capabilities of the array. The adoption of this 2014 Xi Algorithm allowed in excess of 1.1 GW onshore wind development to proceed.

The 0.336 nm budget was issued on a first come, first served basis and no project has been allocated budget since January 2018. The MoD's position is that, at present, the threshold of 0.336 nm has been reached when using the 2014 Xi Engineering Consultants conservative spreadsheet to calculate the cumulative impact of Wind Turbines on the Eskdalemuir seismic array. As this is the only tool the MoD has available it is objecting to all applications to preserve the array's detection capabilities. Any additional applications received subsequent to January 2018 were added to a 'waiting list' for future MoD approval. The current waiting list based on publicly available data corresponds to approximately 2.5 GW of potential onshore wind turbine development. These potential developments would have a significant impact on the 12 GW targeted by The Scottish Government by 2030.

7.2.1 2019-2022 Scottish Government Commissioned Xi Engineering Studies

Between 2019 and 2022 the Scottish Government commissioned Xi Engineering Consultants to deliver a series of technical evaluations and studies. These studies followed a phased approach (Phase 1 through Phase 5) to investigate the potential additional capacity that may be made available were the 2014 algorithm to be revised. These studies confirmed that the algorithm currently used by the MoD to calculate the budget takes a conservative approach and, by design, over-estimates the seismic contribution of each wind turbine.

The Scottish Government has engaged with MoD to seek the MoD's approval of data collected and are seeking agreement that the MoD will adopt this evidence-based approach and adjust the calculation for budget utilisation.

Unlocking potential capacity whilst safeguarding the array has become the task of the reformed Eskdalemuir Working Group (EWG) with the Scottish Government taking role of secretariat and recognises that:

- Safeguarding of the array lies within the MoD policy remit.
- Maximisation of renewable energy deployment lies within the Scottish Government policy remit.

7.2.2 Eskdalemuir Working Group (EWG) scope of works for 2023 to deliver additional capacity for the region.

A draft scope of works has been issued for the Eskdalemuir Working Group (EWG) to produce guidance and is targeting 2023 for delivery. *

The following is a direct excerpt from the Draft Scope of works.

Given current demands on resource for Scottish Government and Ministry of Defence, we suggest a preliminary timeframe of Q4 2023 for finalisation of this guidance.

The document reiterates the MoD refenced section from the ONWPS (2.51.2)

Unlocking potential capacity whilst safeguarding the array will require decisive and meaningful action from the Scottish Government and UK Government. To do so, we must recognise:

- *Safeguarding of the array lies within the MoD policy remit.*
- *Maximisation of renewable energy deployment lies within the Scottish Government policy remit.*

The Draft scope of works for the Eskdalemuir working Group puts forward Proposed Approach(es) specifically.

Following these conversations and reflecting on the results of the recent draft Onshore Wind Policy Statement consultation, as well as the multi-phased technical work, the Scottish Government are minded pursuing the following approaches:

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 0.00836 nm.MW$^{-0.5}$ and ensuring the 0.336 nm threshold is not exceeded.*

**This limit is based on calculations undertaken by Xi Engineering on behalf of the Scottish Government and may be subject to slight variation during formal signoff process by MoD.*

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.

**The revised dates are currently under consideration by the Eskdalemuir Working Group (EWG) – July 2024*

7.2.3 Incorporation of MoD Technical Experts Feedback

Following the MoD subject matter expert's review of the Phase 4 and Phase 5 work packages released in 2022 refinements to the mathematical analysis used to confirm the 'headroom' within the 0.336 nm budget were undertaken. As there was a minor change in the headroom and the Seismic Impact Limit (SIL) is calculated based on the available headroom, Phase 5 was also recalculated based on the refined revisions. For details of the refinement and revision please see documents in Section 6.

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7.3 EKA Budget Technical Background

7.3.1 Relationship between distance and seismic impact

The amplitude of a seismic wave decreases rapidly with distance. This means that turbines built close to the EKA have a far greater impact on the seismic array and consume considerably more seismic budget. A single turbine placed on the border of the 10 km exclusion zone would have the equivalent seismic budget requirement equivalent to approximately 2,000 of the same turbines placed at a distance of 50 km (this calculation is model specific and may vary due to the make and model of the turbine). The installable capacity within the consultation zone can be maximised by avoiding placing turbines close to the EKA.

7.4 Wind farm specifications

The details, layout, and suggested turbine dimensions and power rating are shown in Table 5.

Table 5 – Details of wind turbines at proposed site.

Turbine ID	Eastings	Northings	Distance from Array (km)	Hub Height (m)	Rotor Diameter (m)	Power (MW)
1	287971	618974	41	135	170	7
2	288264	618355	40.51	135	170	7
3	286849	618133	41.78	135	170	7
4	287226	617738	41.3	135	170	7
5	287709	617214	40.68	135	170	7
6	286364	617049	41.92	135	170	7
7	286646	616715	41.55	135	170	7
8	286963	616303	41.13	135	170	7
9	291850	619544	37.59	135	170	7
10	292680	619542	36.83	135	170	7
11	293040	619047	36.3	135	170	7
12	292389	618783	36.8	135	170	7
13	291144	619062	38.06	135	170	7
14	291257	618660	37.81	135	170	7
15	291738	618565	37.33	135	170	7
16	292036	617853	36.8	135	170	7
17	290720	618062	38.1	135	170	7
18	291330	617871	37.46	135	170	7
19	291316	617317	37.29	135	170	7
20	290077	618173	38.74	135	170	7
21	290485	617374	38.09	135	170	7

Based on the proposed rated power of the turbines to be deployed, the Power Seismic Value (PSV) of each turbine was calculated using equation 1 from Phase 5 (see Phase 5 report as referenced in Section 6).

Table 6 shows the PSVs for the rated powers of wind turbines at Ravengill.

Table 6 – Allowable PSVs for the rated power of turbines at Ravengill to conform with a 2.0 GW SIL level.

SIL Target Capacity	Rated Power [MW]	Power Seismic Value (PSV) [nm]
2.0 GW	***7***	***0.015631***

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7.5 Methodology

7.5.1 Budget scenarios assessed

In order to contextualise the implications and demonstrate potential required budget levels, several scenarios have been assessed for different machines. The turbine coordinates and turbine options were coded into MATLAB, and calculations were performed to determine budget levels in line with the mathematical approaches in the reports '*SGV 203 Technical report v12.pdf'* and refined Phase 4 '*AIFCL-101-Phase4-Rev-v13': Field audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions'.*

Seismic measurements of wind turbines include ambient seismic noise. This noise is not attributed to the wind turbines themselves, rather it is produced by a combination of natural and anthropogenic sources. It has been proposed that a background noise measurement could be conducted before wind farms are built and then a subsequent measurement be conducted once the farm is operational. Budget Scenarios 7 – 12 (see below) have been included in the analysis to demonstrate the effect of performing before and after measurement in order to remove background noise. The Budget scenarios modelled are as follows;

1. Siemens — Using Phase 4 published data
2. Senvion — Using Phase 4 published data
3. Vestas — Using Phase 4 published data
4. GE — Using Phase 4 published data
5. Nordex — Using Phase 4 published data
6. Enercon — Using Phase 4 published data
7. Siemens background removed — See Background noise removal section
8. Senvion background removed — See Background noise removal section
9. Vestas background removed — See Background noise removal section
10. GE background removed — See Background noise removal section
11. Nordex background removed — See Background noise removal section
12. Enercon background removed — See Background noise removal section

7.5.2 Background noise removal

It is recommended that a background seismic noise measurement be conducted before the installation of wind turbines at any new wind farm; the background noise could then be subtracted from the operational noise giving a truer value of the contribution of the wind farm to seismicity. This approach is common in acoustic measurements of wind farms. To illustrate the effect that such a measurement campaign may have, tables have been provided where the noise floor has been removed from the algorithms such that the seismic contribution of the wind turbines only come from blade pass and structural resonances. This is very much a best-case scenario and is provided for illustrative purposes only. The authors note that the approach of removing all background noise from the algorithm is contrary to the precautionary approach used to design the 2014 EKA algorithm and that it is likely that some turbines generate noise which exists below the noise floor. Working through real world empirical assessments of this will provide further understanding of how close to this best-case scenario results will be. It will also inform the possible development of a methodology which will not penalise a wind turbine for noise which is not attributable to the wind turbine itself.

7.6 Seismic budget levels for individual turbines

Table 7 – Seismic amplitudes for individual turbines calculated using Phase 4 models with background noise included

With Background Noise Included							
WTG No	Siemens (nm)	Senvion (nm)	Vestas (nm)	GE (nm)	Nordex (nm)	Enercon (nm)	[Candidate Turbine] (nm)
1	0.002853	0.001893	0.003162	0.003344	0.002788	0.002577	0.000578
2	0.002977	0.001976	0.003296	0.003494	0.002908	0.002692	0.000601
3	0.002664	0.001766	0.002958	0.003115	0.002606	0.002403	0.000544
4	0.002778	0.001843	0.003081	0.003254	0.002716	0.002508	0.000565
5	0.002934	0.001947	0.003249	0.003442	0.002866	0.002652	0.000593
6	0.002632	0.001745	0.002924	0.003078	0.002576	0.002374	0.000538
7	0.002718	0.001802	0.003016	0.003181	0.002658	0.002452	0.000554
8	0.002819	0.00187	0.003126	0.003304	0.002756	0.002546	0.000572
9	0.003872	0.002579	0.00426	0.004574	0.003771	0.003524	0.000762
10	0.004154	0.00277	0.004564	0.004915	0.004043	0.003789	0.000814
11	0.004361	0.002911	0.004788	0.005164	0.004244	0.003984	0.000851
12	0.004163	0.002777	0.004574	0.004926	0.004052	0.003797	0.000815
13	0.003709	0.002469	0.004085	0.004378	0.003614	0.003372	0.000733
14	0.003795	0.002528	0.004178	0.004482	0.003697	0.003453	0.000749
15	0.003967	0.002644	0.004363	0.004689	0.003863	0.003613	0.00078
16	0.004167	0.002779	0.004578	0.00493	0.004056	0.003801	0.000816
17	0.003696	0.00246	0.00407	0.004362	0.003601	0.00336	0.000731
18	0.003918	0.00261	0.00431	0.00463	0.003815	0.003567	0.000771
19	0.003981	0.002653	0.004378	0.004706	0.003876	0.003626	0.000782
20	0.003487	0.002319	0.003845	0.00411	0.003399	0.003165	0.000693
21	0.003699	0.002462	0.004074	0.004366	0.003604	0.003363	0.000731

Table 8 - Seismic amplitudes for individual turbines calculated using Phase 4 models with background noise removed

With Background Noise Removed							
WTG No	Siemens (nm)	Senvion (nm)	Vestas (nm)	GE (nm)	Nordex (nm)	Enercon (nm)	[Candidate Turbine] (nm)
1	0.002282	0.001514	0.002529	0.002675	0.00223	0.002062	0.000463
2	0.002382	0.001581	0.002637	0.002795	0.002326	0.002154	0.000481
3	0.002131	0.001413	0.002366	0.002492	0.002085	0.001922	0.000435
4	0.002222	0.001474	0.002465	0.002603	0.002173	0.002006	0.000452
5	0.002347	0.001558	0.002599	0.002753	0.002293	0.002121	0.000474
6	0.002106	0.001396	0.002339	0.002462	0.002061	0.001899	0.000431
7	0.002174	0.001442	0.002413	0.002545	0.002126	0.001962	0.000443
8	0.002255	0.001496	0.002501	0.002643	0.002205	0.002037	0.000458
9	0.003097	0.002063	0.003408	0.00366	0.003017	0.002819	0.00061
10	0.003323	0.002216	0.003651	0.003932	0.003235	0.003031	0.000651

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With Background Noise Removed							
WTG No	Siemens (nm)	Senvion (nm)	Vestas (nm)	GE (nm)	Nordex (nm)	Enercon (nm)	[Candidate Turbine] (nm)
11	0.003489	0.002329	0.00383	0.004131	0.003395	0.003187	0.000681
12	0.003331	0.002221	0.003659	0.003941	0.003242	0.003038	0.000652
13	0.002967	0.001975	0.003268	0.003502	0.002891	0.002698	0.000586
14	0.003036	0.002022	0.003342	0.003586	0.002958	0.002762	0.000599
15	0.003173	0.002115	0.00349	0.003751	0.00309	0.002891	0.000624
16	0.003333	0.002223	0.003662	0.003944	0.003244	0.00304	0.000653
17	0.002957	0.001968	0.003256	0.00349	0.002881	0.002688	0.000584
18	0.003134	0.002088	0.003448	0.003704	0.003052	0.002854	0.000617
19	0.003185	0.002123	0.003502	0.003765	0.003101	0.002901	0.000626
20	0.002789	0.001855	0.003076	0.003288	0.002719	0.002532	0.000554
21	0.002959	0.00197	0.003259	0.003493	0.002883	0.00269	0.000585

7.7 Full individual turbine seismic impact limit results

Table 9 – TMRs for each individual turbine using worst-case Phase 4 and candidate models

WTG No	Background Included TMR		Background Removed TMR	
	Worst-Case Model	Candidate Model	Worst-Case Model	Candidate Model
1	4.674	27.033	5.843	33.791
2	4.473	26.02	5.592	32.526
3	5.017	28.734	6.272	35.917
4	4.804	27.679	6.005	34.599
5	4.542	26.365	5.677	32.956
6	5.079	29.036	6.349	36.295
7	4.914	28.226	6.143	35.282
8	4.731	27.317	5.914	34.147
9	3.417	20.501	4.271	25.626
10	3.181	19.212	3.976	24.016
11	3.027	18.362	3.784	22.953
12	3.173	19.173	3.967	23.966
13	3.57	21.325	4.463	26.656
14	3.487	20.88	4.359	26.1
15	3.333	20.048	4.167	25.06
16	3.171	19.158	3.963	23.948
17	3.583	21.394	4.479	26.743
18	3.376	20.279	4.22	25.349
19	3.321	19.983	4.152	24.979
20	3.803	22.561	4.754	28.201
21	3.58	21.379	4.475	26.723