Xi Engineering Consultants

Clyde South Wind Farm, Eskdalemuir Seismic Array Considerations

Seismic Budget & SIL Analysis

Client: Renewco Power

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Document Summary

This Report is prepared on behalf of Renewco Power, to assess the potential vibration impact of the Clyde South Wind Farm on the MoD's Eskdalemuir Seismic Array using quantified operational turbine data.

The Clyde South Wind Farm site lies within the Eskdalemuir Consultation Zone and is yet to be allocated a seismic budget. Two composite sites of Clyde South Wind Farm were considered: Crookedstane (3 turbines) and Mid Height/Lion Hill (6 turbines). An analysis was carried out of the 9 turbines in the proposed Clyde South Wind Farm to determine the seismic budget requirement as well as the seismic impact based on three potential SIL deployments (1.0, 2.0 and 2.5 GW).

18 models were run based on *Refined Phase 4 'AIFCL-101-Phase4-Rev-v13* including the current MoD algorithm, Phase 4 synthetic models and directly measured data (SG155).

Seismic Budget Findings

The estimated seismic budget required for Clyde South Wind Farm was found to range between 0.032405 nm using the current MoD algorithm down to 0.009464 nm for the SG155 directly measured model with background noise included. Budget requirements are further reduced if background noise is removed.

Seismic Impact Limit Analysis Findings

To prevent sites close to the array from disproportionately using available Seismic Vibraiton 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 be between 0.00836 nm·$MW^{-0.5}$ (for a 1.0 GW deployment) and 0.00528 nm·$MW^{-0.5.}$ (for a 2.5 GW deployment) will likely be set for all new wind turbines installed in the Eskdalemuir Consultation Zone.

Turbines at Clyde South Wind Farm were analysed using all Phase 4 and directly-measured models where it was found that all 9 turbines can be built without requirement for mitigation for any of the potential SILs.

Action	Name	Date	Version	Amendment
Originator	Dr M. Chung	21/02/25	v1	Creation
Review	R. Horton	27/02/25	v2-3	Review & Formatting
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Review	A. Dresser	04/03/25	v5	Review & Issue
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1. Introduction

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 appendix 9.1.

Xi Engineering Consultants (Xi), as technical experts in vibration, noise, and advanced 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 Clyde South Wind Farm site lies within the Eskdalemuir Consultation Zone and has yet to be allocated a seismic budget.

Work conducted by the Scottish Government have 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, the SIL will likely be set between $0.00836\ nm \cdot MW^{-0.5}$ and $0.00528\ nm \cdot MW^{-0.5}$.

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, Clyde South 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 the Appendix as well as publicly available documents listed in reference section 8.

In line with the resulting policy and reporting procedures, Renewco Power need to demonstrate understanding of the absolute level of seismic budget required by the site - taking these figures into consideration in ongoing planning of the site and modifying where necessary in order to remain within budget.

With this considered, this report examines:

1. The seismic budget requirements for Clyde South Wind Farm
2. Which turbines will meet potential Seismic Impact Limits for deployments of 1.0, 2.0 and 2.5 GW.

Clyde South Wind Farm is planned to consist of three component sites that are geographically separated: Hartside, Crookedstane and Mid Height/Lion Hill. As requested, this report only considers the seismic impact of Crookedstane and Mid Height/Lion Hill, the southern component sites. The content of this report is intended to be utilised in the Renewco Power EIA Scoping Report for Clyde South Wind Farm.

2. Definitions

In this report, the following nomenclature in Table 1 is employed for clarity:

Acronym	Definition	Notes
SIL	Seismic Impact Limit	Constant 0.00836 nm.MW$^{-0.5}$ for 1.0 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.

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

3. Wind Farm Specifications

3.1. Candidate Machine

At this stage of development, the candidate machine is not fixed, and so multiple models have been considered. The rated power of the turbines is expected to fall somewhere between 4.5 and 7.0 MW. In this report, the analysis used the worst-case option and assumed all turbines were 4.5 MW.

3.2. Wind farm specifications

The component sites of Clyde South Wind Farm, Crookedstane and Mid Height/Lion Hill are proposed to consist of 3 and 6 turbines, respectively, and each proposed to be a minimum of 4.5 MW, providing an overall capacity of 40.5 MW (see Table 3), with a maximum tip height of 180 m. As the current layout of the proposed Clyde South Wind Farm is between 29.0 km and 31.5 km from the EKA, it is likely to be subject to a SIL, if adopted. Based on the proposed minimum 4.5 MW turbines to be deployed at Clyde South Wind Farm, the Power Seismic Value (PSV) of each turbine was calculated using equation 1 from Phase 5 (see section 8). As all turbines at Clyde South Wind Farm are proposed to have the same power output, the PSV for each turbine is between 0.017725 nm, for a 1.0 GW SIL limit, and 0.011210 nm for a 2.5 GW SIL Limit (Table 2).

SIL Target Capacity	Power Seismic Value (PSV) for a 4.5 MW Turbine
1.0 GW	0.017725 nm
2.0 GW	0.012533 nm
2.5 GW	0.011210 nm

Table 2 – Allowable PSVs for a 4.5 MW turbine to conform with different SIL levels.

The proposed Clyde South Wind Farm consists of 9 turbines (3 at Crookedstane and 6 at Mid Height/Lion Hill) with a maximum tip height of 180 m and a rotor diameter of 155 m. The nearest turbine is 29.0 km from the EKA. Specific turbine locations and dimensions at are shown in Table 3.

Component Site	Turbine ID	Eastings	Northings	Range (km)	Hub Height (m)	Rotor diameter (m)	Power (MW)
Crookedstane	1	297267	615081	30.93	102.5	155.0	4.5
	2	296929	614381	31.03			
	3	296292	613917	31.51			
Mid Height/ Lion Hill	4	297090	611633	30.16			
	5	296591	611026	30.52			
	6	297336	611307	29.85			
	7	297750	611037	29.38			
	8	297236	610578	29.80			
	9	298041	610656	29.02			

Table 3 – Clyde South Wind Farm turbine details

4. Methodology

4.1. 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 9 – 16 & 18 (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. Standard EKA algorithm	Using the Current MoD 'worst case' algorithm.
2. Siemens	Using Phase 4 published data
3. Senvion	Using Phase 4 published data
4. Vestas	Using Phase 4 published data
5. GE	Using Phase 4 published data
6. Nordex	Using Phase 4 published data
7. Enercon	Using Phase 4 published data
8. Gamesa	Using Phase 4 published data
9. Standard EKA background removed	See Background noise removal section
10. Siemens background removed	See Background noise removal section
11. Senvion background removed	See Background noise removal section
12. Vestas background removed	See Background noise removal section
13. GE background removed	See Background noise removal section
14. Nordex background removed	See Background noise removal section
15. Enercon background removed	See Background noise removal section
16. Gamesa background removed	See Background noise removal section
17. Siemens Gamesa 155	Data from Manufacturer measured by XiEC
18. SG155 Background removed	See Background noise removal section

The SG155 (Scenarios 17 + 18) was measured outside of the Eskdalemuir region (Sweden). To correct the seismic measurements, conservative geology normalisation was applied to the measurements to translate the data to Eskdalemuir geology.

4.2. 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.

5. Results

This section summarises results based on assumed 155 m rotor diameter, 102.5 m hub height and 180 m tip height. Seismic budget calculations show the overall seismic noise contributions of turbines installed at Clyde South Wind Farm as well as the individual turbine contributions. The SIL calculations show if all turbines could be built at Clyde South Wind Farm while meeting the SIL for different deployments (1.0, 2.0 and 2.5 GW) and, if not, how many turbines would require mitigation to meet the SIL.

5.1. The seismic budget requirements for Clyde South Wind Farm

The following table (Table 4) shows the seismic budget levels of the Wind Farm as a whole site using the various potential turbine options, with and without background noise, respectively. In this instance, all 9 turbines were analysed and summed (both Crookedstane and Mid Height/Lion Hill). The seismic contributions of the individual component sites can be found in the Appendix (Section 9.3). Highest seismic results are indicated in red while the lowest are indicated in green.

The seismic budget levels for individual turbines are listed in the Appendix (Section 9.3) using the various potential turbine options, with and without background noise, respectively.

Clyde South budget allocation:		TBC	
Model		With background noise	Without background noise
		Seismic level (nm)	Seismic level (nm)
Standard EKA Algorithm		0.032405	0.029773
Phase 4 Synthetic models	Siemens	0.020163	0.015914
	Senvion	0.014434	0.008255
	Vestas	0.022102	0.014240
	GE	0.022392	0.018887
	Nordex	0.016169	0.009912
	Enercon	0.015515	0.008806
	Gamesa	0.029550	0.018170
Scaled direct measurements	SG155	0.009464	0.006256

Table 4 – Seismic results of scenarios modelled using Phase 4 data plus SG155 (all results are in nm).

5.2. Seismic Impact Limit Turbine Mitigation Ratio Results

The tables below show the Seismic Impact Limit analysis results for deployments of 1.0, 2.0 and 2.5 GW using Phase 4 synthetic models as well as scaled measured data (Siemens SG155). Table 5 shows results from models including background noise whilst Table 6 shows results with background noise removed.

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. A TMR greater than 1 indicates that the turbine will not require mitigation for the given SIL while a TMR less than 1 indicates that the turbine will likely require mitigation to meet the given SIL.

In the tables below, results coloured green indicate no mitigation is required for the installation of all turbines at Clyde South Wind Farm according to the model and given SIL. Results coloured red indicate some mitigation is required to meet the given SIL.

Full TMR results for each individual turbine and model can be seen in Appendix 9.4.

With background noise	Deployment (*Power Seismic Value*)								
	1.0 GW (*0.017725 nm*)			2.0 GW (*0.012533 nm*)			2.5 GW (*0.011210 nm*)		
Model	*No. of turbines requiring mitigation*	*Highest TMR*	*Lowest TMR*	*No. of turbines requiring mitigation*	*Highest TMR*	*Lowest TMR*	*No. of turbines requiring mitigation*	*Highest TMR*	*Lowest TMR*
Standard EKA	0	1.884	1.452	0	1.521	1.256	3	1.192	0.918
Siemens	0	3.011	2.344	0	2.440	2.011	0	1.904	1.483
Senvion	0	4.220	3.265	0	3.412	2.815	0	2.669	2.065
Vestas	0	2.750	2.136	0	2.227	1.836	0	1.739	1.351
GE	0	2.715	2.109	0	2.198	1.812	0	1.717	1.334
Nordex	0	3.757	2.921	0	3.044	2.509	0	2.376	1.847
Enercon	0	3.949	3.023	0	3.180	2.628	0	2.497	1.912
Gamesa	0	2.050	1.602	0	1.664	1.371	0	1.297	1.013
SG155	0	6.565	4.900	0	5.236	4.346	0	4.152	3.099

Table 5 – Summary of SIL analysis for models with background noise included - Note red denotes the SIL limit is NOT met.

Without background noise	Deployment (*Power Seismic Value*)								
	1.0 GW (*0.017725 nm*)			2.0 GW (*0.012533 nm*)			2.5 GW (*0.011210 nm*)		
Model	*No. of turbines requiring mitigation*	*Highest TMR*	*Lowest TMR*	*No. of turbines requiring mitigation*	*Highest TMR*	*Lowest TMR*	*No. of turbines requiring mitigation*	*Highest TMR*	*Lowest TMR*
Standard EKA	0	2.052	1.580	0	1.655	1.367	1	1.298	0.999
Siemens	0	3.805	2.977	0	3.089	2.544	0	2.406	1.883
Senvion	0	7.367	5.715	0	5.964	4.918	0	4.659	3.615
Vestas	0	4.251	3.325	0	3.453	2.844	0	2.689	2.103
GE	0	3.215	2.503	0	2.605	2.147	0	2.033	1.583
Nordex	0	6.094	4.786	0	4.957	4.080	0	3.854	3.027
Enercon	0	7.031	5.281	0	5.621	4.660	0	4.447	3.340
Gamesa	0	3.301	2.627	0	2.698	2.216	0	2.088	1.662
SG155	0	10.189	7.269	0	7.981	6.502	0	6.444	4.597

Table 6 – Summary of SIL analysis for models with background noise removed - Note red denotes the SIL limit is NOT met.

5.3. Mitigation

As can be seen in Table 5 and Table 6, all turbines are above a Turbine Mitigation Ratio of 1, with the exception of the current MoD algorithm (Standard EKA) for a deployment of 2.5 GW when both including and removing background noise.

The current standard algorithm would cause a lowest TMR of 0.918 (2.5 GW SIL, and 3 turbines potentially affected including background noise) and 0.999 (2.5 GW and 1 turbine potentially affected without background noise), as can be seen in Row 1 of Tables 5 & 6 respectively. This will likely be irrelevant as policy is currently being drafted to move away from the worst-case current standard algorithm to use empirical data, i.e. Tables 5 & 6 excluding the first row.

For the turbines that fall below a TMR of 1, the lowest TMR was found to be 0.918. As this TMR value is close to 1, engineered mitigation measures or curtailment would both be effective at enabling these turbines to meet the SIL, if required. Considering this analysis uses the worst case (i.e. lowest rated power of 4.5 MW) and all other models calculated TMRs above 1, the likelihood of mitigation being required is low.

6. Discussion

6.1. Modelled Budget Requirements

The mathematical approach used in this document assesses the level of seismic budget required to build Clyde South Wind Farm dependant on specific models and inclusion or removal of background noise.

The required seismic budget ranges from 0.032405 nm using the current MoD algorithm down to the predicted 0.006256 nm when using data from the SG155 model with the background noise removed. The budget range based on Phase 4 measurements including background is between 0.029550 nm for the no longer available Gamesa Machine and 0.014434 nm for the Senvion Machine. If the 'worst case' of the Phase 4 measured turbines that are currently available on the market were to be allocated, the GE turbine with a budget requirement of 0.022392 nm would be used.

6.2. Modelled SIL Requirements

The Seismic Impact Levels for the Clyde South Wind Farm have been assessed for a range of 1.0 GW to 2.5 GW deployment within the Eskdalemuir region. The 1.0 GW and 2.5 GW SIL limits represent a turbine SIL of 0.00836 nm.$MW^{-0.5}$ and 0.00528 nm·$MW^{-0.5}$ respectively. It should be noted that these figures might change during the SG and MoD signoff process. For the proposed minimum 4.5 MW turbines at Clyde South Wind Farm the permitted PSVs are between 0.017725 nm and 0.011210 nm (again for 1.0 GW and 2.5 GW respectively).

All turbines at Clyde South Wind Farm are above the Turbine Mitigation Ratio, with the exception of the current MoD algorithm (Standard EKA) when both including and removing background noise. As stated above, the current MoD algorithm is due to be superseded by policy currently being drafted and will therefore no longer apply.

For the turbines that fall below a TMR of 1, the lowest TMR was found to be 0.918. As this TMR value is close to 1, engineered mitigation measures or curtailment (see section below) would both be effective at enabling these turbines to meet the SIL, if required. Considering this analysis uses the worst case (i.e. lowest rated power of 4.5 MW) and all other models except for the current MoD algorithm (a model which will no longer be applicable in this analysis) calculated TMRs above 1, the likelihood of mitigation being required is low.

6.3. Mitigation Options

It is feasible to install additional engineered mitigation measures that could reduce the seismic signatures. The following seismic reduction strategies could potentially be utilised, if required:

1. Tuned mass damper.
2. Foundation isolation.
3. Control based mitigation.

Further desktop calculations and analyses would be recommended should this be considered, providing an estimate of seismic mitigation and curtailment strategies' requirements.

7. Conclusion

- Clyde South Wind Farm, as proposed, represents 9 turbines from its component sites Crookedstane (3 turbines) and Mid Height/Lion Hill (6 turbines) each with a minimum power rating of 4.5 MW and has an average distance to the Eskdalemuir seismic array of ~30.2 km.
- Clyde South Wind Farm has not yet been allocated a seismic budget.
- The levels of Seismic Budget required by Clyde South Wind Farm have been calculated using the best available science and most up to date data in the public domain, as well as measured data from the SG155 machine.
- The levels of Seismic Impact Limit have been calculated using the best available science and utilising all available data and Phase 4 measurements.
- Due to the ~30.2 km distance from the array of Clyde South Wind Farm, great consideration regarding the SIL must be given, particularly for higher deployments (i.e. a 2.5 GW SIL).
- For all models, the analysis shows that all turbines could be built within the 1.0 GW – 2.5 GW Seismic Impact Limit under assessment by the EWG without mitigation except for the current MoD algorithm model, which failed for a 2.5 GW deployment.
- The scenarios where the TMR falls below 1 relate to the EKA Standard Algorithm only. This is likely to be superseded by policy currently being drafted and these scenarios are therefore very unlikely.
- Renewco Power would minimise seismic levels through performing candidate turbine, before and after measurements.

8. 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 refresh 2021: consultative draft

All publicly available documents can be downloaded here

9. Appendix

9.1. 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 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.

9.1.1. 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.

9.1.2. 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*

9.1.3. 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 section8.

9.2. EKA Budget Technical Background

9.2.1. 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.

9.3. Seismic Budget Levels for Composite Sites and Individual Turbines

Crookedstane (3 turbines)			
Model		**With background noise**	**Without background noise**
		Seismic level (nm)	**Seismic level (nm)**
Standard EKA Algorithm		0.016902	0.015525
Phase 4 Synthetic models	Siemens	0.010563	0.008353
	Senvion	0.007542	0.004318
	Vestas	0.011566	0.007474
	GE	0.011719	0.009893
	Nordex	0.008464	0.005211
	Enercon	0.008072	0.004545
	Gamesa	0.015502	0.009603
Scaled direct measurements	SG155	0.004872	0.003160

Table 7 – Total seismic amplitudes from different models for Crookedstane. Red indicates highest amplitude while green indicates the lowest.

Mid Height/Lion Hill (6 turbines)			
Model		**With background noise**	**Without background noise**
		Seismic level (nm)	**Seismic level (nm)**
Standard EKA Algorithm		0.027649	0.025404
Phase 4 Synthetic models	Siemens	0.017175	0.013546
	Senvion	0.012308	0.007036
	Vestas	0.018834	0.012121
	GE	0.019080	0.016088
	Nordex	0.013776	0.008432
	Enercon	0.013250	0.007542
	Gamesa	0.025157	0.015425
Scaled direct measurements	SG155	0.008114	0.005400

Table 8 – Total seismic amplitudes from different models for Mid Height/Lion Hill. Red indicates highest amplitude while green indicates the lowest.

With Background Included									
WTG No	Standard EKA Algorithm (nm)	Siemens (nm)	Senvion (nm)	Vestas (nm)	GE (nm)	Nordex (nm)	Enercon (nm)	Gamesa (nm)	SG155 (nm)
Crookedstane									
1	0.009981	0.006232	0.004452	0.006825	0.006916	0.004994	0.004769	0.009143	0.002884
2	0.009878	0.006170	0.004407	0.006757	0.006846	0.004945	0.004718	0.009054	0.002851
3	0.009406	0.005887	0.004200	0.006445	0.006529	0.004717	0.004489	0.008645	0.002700
Mid Height/Lion Hill									
4	0.010826	0.006737	0.004822	0.007384	0.007482	0.005402	0.005182	0.009873	0.003159
5	0.010425	0.006497	0.004646	0.007118	0.007213	0.005208	0.004985	0.009527	0.003028
6	0.011186	0.006952	0.004980	0.007622	0.007723	0.005575	0.005359	0.010184	0.003277
7	0.011746	0.007286	0.005226	0.007993	0.008096	0.005846	0.005635	0.010667	0.003463
8	0.011244	0.006986	0.005005	0.007660	0.007761	0.005603	0.005387	0.010234	0.003296
9	0.012207	0.007560	0.005429	0.008299	0.008403	0.006068	0.005863	0.011064	0.003617

Table 9 – Individual seismic Budget calculations for Clyde South Wind Farm

No Background									
WTG No	Standard EKA Algorithm (nm)	Siemens (nm)	Senvion (nm)	Vestas (nm)	GE (nm)	Nordex (nm)	Enercon (nm)	Gamesa (nm)	SG155 (nm)
Crookedstane									
1	0.009169	0.004926	0.002548	0.004407	0.005837	0.003072	0.002690	0.005656	0.001878
2	0.009074	0.004878	0.002523	0.004365	0.005779	0.003043	0.002659	0.005604	0.001853
3	0.008639	0.004658	0.002406	0.004170	0.005513	0.002908	0.002521	0.005369	0.001740
Mid Height/Lion Hill									
4	0.009947	0.005318	0.002758	0.004757	0.006312	0.003312	0.002940	0.006073	0.002086
5	0.009577	0.005132	0.002658	0.004591	0.006087	0.003198	0.002821	0.005875	0.001986
6	0.010278	0.005484	0.002847	0.004907	0.006513	0.003414	0.003048	0.006250	0.002176
7	0.010793	0.005742	0.002986	0.005139	0.006824	0.003573	0.003216	0.006523	0.002319
8	0.010331	0.005511	0.002861	0.004930	0.006545	0.003430	0.003065	0.006278	0.002191
9	0.011218	0.005954	0.003101	0.005331	0.007080	0.003703	0.003356	0.006746	0.002438

Table 10 – Individual seismic Budget calculations for Clyde South Wind Farm without background noise.

9.4. Full Individual Turbine Seismic Impact Limit Results

		With Background Noise									Without Background Noise								
WTG No	PSV (nm)	Standard EKA TMR	Siemens TMR	Senvion TMR	Vestas TMR	GE TMR	Nordex TMR	Enercon TMR	Gamesa TMR	SG155 TMR	Standard EKA TMR	Siemens TMR	Senvion TMR	Vestas TMR	GE TMR	Nordex TMR	Enercon TMR	Gamesa TMR	SG155 TMR
1	0.017725	2.844	3.981	2.597	2.563	3.549	3.717	1.939	6.146	2.844	1.933	3.598	6.955	4.022	3.036	5.770	6.590	3.134	9.439
2	0.017725	2.873	4.022	2.623	2.589	3.585	3.757	1.958	6.217	2.873	1.953	3.633	7.026	4.061	3.067	5.825	6.666	3.163	9.567
3	0.017725	3.011	4.220	2.750	2.715	3.757	3.949	2.050	6.565	3.011	2.052	3.805	7.367	4.251	3.215	6.094	7.031	3.301	10.189
4	0.017725	1.637	2.631	3.676	2.401	2.369	3.281	3.420	1.795	5.611	1.782	3.333	6.427	3.726	2.808	5.352	6.029	2.919	8.497
5	0.017725	1.700	2.728	3.815	2.490	2.457	3.403	3.555	1.861	5.854	1.851	3.454	6.668	3.861	2.912	5.542	6.284	3.017	8.923
6	0.017725	1.584	2.550	3.559	2.325	2.295	3.179	3.308	1.740	5.408	1.724	3.232	6.225	3.612	2.722	5.192	5.816	2.836	8.144
7	0.017725	1.509	2.433	3.392	2.217	2.189	3.032	3.146	1.662	5.118	1.642	3.087	5.935	3.449	2.597	4.961	5.511	2.717	7.643
8	0.017725	1.576	2.537	3.541	2.314	2.284	3.163	3.290	1.732	5.377	1.716	3.216	6.194	3.595	2.708	5.167	5.783	2.824	8.090
9	0.017725	1.452	2.344	3.265	2.136	2.109	2.921	3.023	1.602	4.900	1.580	2.977	5.715	3.325	2.503	4.786	5.281	2.627	7.269

Table 11 – TMR for Scottish Government 1.0 GW SIL Individual Turbine – Note red denotes the SIL limit is NOT met.

		With Background Noise									Without Background Noise								
WTG No	PSV (nm)	Standard EKA TMR	Siemens TMR	Senvion TMR	Vestas TMR	GE TMR	Nordex TMR	Enercon TMR	Gamesa TMR	SG155 TMR	Standard EKA TMR	Siemens TMR	Senvion TMR	Vestas TMR	GE TMR	Nordex TMR	Enercon TMR	Gamesa TMR	SG155 TMR
1	0.012533	1.256	2.011	2.815	1.836	1.812	2.509	2.628	1.371	4.346	1.367	2.544	4.918	2.844	2.147	4.080	4.660	2.216	6.674
2	0.012533	1.269	2.031	2.844	1.855	1.831	2.535	2.656	1.384	4.396	1.381	2.569	4.968	2.871	2.169	4.119	4.713	2.236	6.765
3	0.012533	1.332	2.129	2.984	1.945	1.920	2.657	2.792	1.450	4.642	1.451	2.690	5.209	3.006	2.273	4.309	4.971	2.334	7.205
4	0.012533	1.464	2.353	3.288	2.147	2.119	2.935	3.059	1.606	5.019	1.594	2.981	5.748	3.332	2.512	4.787	5.392	2.610	7.600
5	0.012533	1.521	2.440	3.412	2.227	2.198	3.044	3.180	1.664	5.236	1.655	3.089	5.964	3.453	2.605	4.957	5.621	2.698	7.981
6	0.012533	1.417	2.280	3.183	2.080	2.053	2.843	2.958	1.557	4.837	1.542	2.891	5.568	3.231	2.434	4.643	5.202	2.537	7.284
7	0.012533	1.350	2.176	3.034	1.983	1.958	2.712	2.814	1.486	4.578	1.469	2.761	5.308	3.085	2.323	4.437	4.929	2.431	6.836
8	0.012533	1.410	2.269	3.167	2.070	2.043	2.829	2.943	1.549	4.810	1.535	2.877	5.540	3.215	2.422	4.622	5.173	2.525	7.236
9	0.012533	1.299	2.097	2.920	1.910	1.887	2.613	2.704	1.433	4.383	1.413	2.663	5.112	2.974	2.239	4.281	4.724	2.350	6.502

Table 12 – TMR for Scottish Government 2.0 GW SIL Individual Turbine – Note red denotes the SIL limit is NOT met.

		With Background Noise									Without Background Noise								
WTG No	PSV (nm)	Standard EKA TMR	Siemens TMR	Senvion TMR	Vestas TMR	GE TMR	Nordex TMR	Enercon TMR	Gamesa TMR	SG155 TMR	Standard EKA TMR	Siemens TMR	Senvion TMR	Vestas TMR	GE TMR	Nordex TMR	Enercon TMR	Gamesa TMR	SG155 TMR
1	0.011210	1.123	1.799	2.518	1.643	1.621	2.245	2.351	1.226	3.887	1.223	2.276	4.399	2.543	1.920	3.649	4.168	1.982	5.970
2	0.011210	1.135	1.817	2.544	1.659	1.637	2.267	2.376	1.238	3.932	1.235	2.298	4.444	2.568	1.940	3.684	4.216	2.000	6.050
3	0.011210	1.192	1.904	2.669	1.739	1.717	2.376	2.497	1.297	4.152	1.298	2.406	4.659	2.689	2.033	3.854	4.447	2.088	6.444
4	0.011210	1.035	1.664	2.325	1.518	1.498	2.075	2.163	1.135	3.549	1.127	2.108	4.065	2.356	1.776	3.385	3.813	1.846	5.374
5	0.011210	1.075	1.725	2.413	1.575	1.554	2.152	2.249	1.177	3.702	1.170	2.184	4.217	2.442	1.842	3.505	3.974	1.908	5.643
6	0.011210	1.002	1.612	2.251	1.471	1.452	2.011	2.092	1.101	3.421	1.091	2.044	3.937	2.285	1.721	3.283	3.678	1.794	5.151
7	0.011210	0.954	1.539	2.145	1.402	1.385	1.918	1.989	1.051	3.237	1.039	1.952	3.754	2.181	1.643	3.138	3.486	1.719	4.834
8	0.011210	0.997	1.605	2.240	1.463	1.444	2.001	2.081	1.095	3.401	1.085	2.034	3.918	2.274	1.713	3.268	3.658	1.786	5.117
9	0.011210	0.918	1.483	2.065	1.351	1.334	1.847	1.912	1.013	3.099	0.999	1.883	3.615	2.103	1.583	3.027	3.340	1.662	4.597

Table 13 – TMR for Scottish Government 2.5 GW SIL Individual Turbine – Note red denotes the SIL limit is NOT met.