

Eskdalemuir Wind Turbine Seismic Vibration

Phase 4 REV: Field Audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions - issue incorporating feedback from Ministry of Defence Subject Matter Expert

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Document Summary

This report is a revision of the SGV-204-TechnicalReport-v12 now incorporating feedback from the Ministry of Defence's Subject Matter Expert.

Seismic sensors were used to measure the amplitude of seismic ground vibration produced by wind turbines at seven wind farms in the Eskdalemuir consultation zone. The data are normalised to produce conservative spectra that represent the source term of a single wind turbine measured at a distance of 1 km. The normalised spectra were fit by synthetic spectra that represent most of the major wind turbine manufacturers in the consultation zone; Nordex, Siemens, GE, Gamesa, Enercon, Vestas and Senvion (EWT was the only known turbine manufacturer not measured, of which there is a single turbine with a capacity of 500 kW). In the previous (v12) issue of this report, the fitting of the synthetic spectra was un-weighted; this report incorporates the re-fitting of the synthetic spectra after weighting the data using a frequency-distance weighting function appropriate for a wind turbine 10 km from the Eskdalemuir seismic array (EKA). This refitting of the synthetic data was as a direct result of Ministry of Defence (MoD) expert input. Using the Frequency-Distance Weighting Function (FDWF) for a distance of 10 km means that spectra are best fitted for turbines that are likely most impactful on the detection capabilities of EKA.

In this issue (version AIFCL-101-Phase4-Rev13) the budget list was re-audited by both Scottish Government and Xi Engineering Consultants to best represent the state of planning at the time of writing. Consistent with the Phase 5 Report (SGV-205-LimitSet-TechReport-v13) the cumulative seismic budget up to and including Scotston Bank was assessed and head-room within the 0.336 nm budget threshold was calculated. In cases where the turbine manufacturer for a given wind farm was unknown, the predicted seismic ground vibration was calculated using synthetic spectra representing turbine types likely to be used in the consultation zone in the future, and the highest value taken. Based on these assumptions, the cumulative budget up to and including Scotston Bank is 0.20756nm and there is 0.26422 nm of budget head-room.

This report supersedes SGV-204 Technical Report v12.

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Contents

1. Definition of terms.....	5
2. Introduction.....	5
3. Technical Background.....	7
4. Summary of measurements	8
4.1. Background noise at Solwaybank and Minnygap.....	10
4.2. Background noise and extrapolation at Harestanes	13
5. Measured data compared to algorithm estimates.....	14
6. Extrapolation to entire budget list.....	15
6.1.1. Two manufacturers at Craig wind farm	17
6.1.2. Two hub heights at Glenkerie	19
6.1.3. Unknown and unmeasured turbines	19
6.1.4. Budget list assumptions.....	19
6.2. Results.....	20
7. Discussion	20
7.1. Uncertainties and assumptions.....	20
7.2. Implications for head room and further capacity	21
7.3. Implication of exclusion zone.....	21
7.4. Background noise levels.....	21
8. Conclusion	22
9. Appendix A – Coefficients used to represent turbines by manufacturers.	23
10. Appendix B – Fitting of Synthetic Spectra to measurement at each wind farm.....	24
11. Appendix C Assessment of budget list.....	29
12. Appendices D.1-D.7 – Measurement Reports for each Wind Farm	32
13. Appendix E – Summary of Results from Phase 2	33

1. Definition of terms

Capacity power	Electric generation capacity for a given turbine or cumulative turbines based on their rated power
EKA	Eskdalemuir Seismic Array
Eskdalemuir Consultation Zone	The area with 50 km of the Eskdalemuir Seismic Array
FDWF	Frequency-distance weighting function which accounts for the variation in transmission with distance over a range of frequencies, to account for the sensitivity to signals detected at the array.
List	Wind farms submitted to the planning process and have a turbine(s) in the Eskdalemuir Consultation Zone
Seismic power	Power Spectral Density (PSD) of ground vibration.
Threshold	The ground vibration amplitude at the Eskdalemuir Seismic Array permitted to be produced by all wind turbines in the Eskdalemuir Consultation Zone. The Threshold is 0.336 nm

2. Introduction

With good wind conditions and proximity to population centres, southern Scotland has excellent potential for onshore wind electricity generation. However, much of this region falls within the Eskdalemuir consultation zone and limits wind development. The zone is formed by a 50 km radius (representing nearly 10% of Scotland's total land area) surrounding the Eskdalemuir seismometer array station (EKA) which is operated by the Ministry of Defence. To protect the EKA, wind turbines built in the area must operate within a seismic ground vibration budget (or threshold) of 0.336nm. Each turbine currently contributes to the budget using a predictive algorithm based upon a worst-case hypothetical turbine. Using this hypothetical turbine the vibration budget of 0.336nm has been reached. Currently no further wind turbine development in the region is possible, preventing access to the significant wind resource available in the area.

By design, the current predictive algorithm used to represent the worst-case turbine includes factors of safety appropriate to the data sample size available at the time, ensuring that the algorithm over-estimates the cumulative seismic ground vibrations produced by wind turbines and does not compromise the detection capabilities of EKA. The approach adopted here is to increase the available data set and reduce, but not remove, the safety factor appropriately. Directly measuring the seismic output of a greater number of turbines in the consultation zone, and reducing the safety factor applied, should allow further wind capacity to be deployed within the region.

Due to the pressing nature of the Climate Crisis, to retrospectively measure every wind turbine site within the consultation zone is not viable due to both time and financial constraints, given the number of turbines deployed within the region. Therefore, seven wind farms were chosen that contain a high proportion of wind turbine make and models in the consultation zone. The wind farm selection was informed by work presented in the report *Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements*

(SGV_203_Tech_Report_v12). The wind farms measured in this phase of work were Craig Hill, Langhope Rig, Harestanes, Ewe Hill, Glenkerie, Minnygap and Solwaybank. The predicted cumulative seismic ground vibration amplitude of turbines that have been constructed and are operational at the time of measurement (i.e., not including those consented or in planning but not yet built) is 0.161 nm as estimated by the current algorithm. The wind turbine models at the wind farms reported here combined with those previously measured at Middle Muir and Clyde contribute a total of 0.153 nm of the 0.161 nm when using the current algorithm, thus capturing the vast majority of the budget contribution with these measurements.

The focus of the work presented here is to use measured data to reduce the level of uncertainty in calculating the contribution of wind turbines provided by the current algorithm. When decisions on data handling are required, a conservative approach to ensure that the detection capabilities of EKA are protected. The work presented in this revision incorporates Ministry of Defence's Subject Matter Expert feedback. This report is the updated Phase 4 Report with three modifications and supersedes SGV-204-Technical Report-v12:

1. A re-audit of the Eskdalemuir List based on planning assumptions at the time of writing.
2. Re-fitting of synthetic spectra weighted using the frequency-distance weighting function appropriate for a wind turbine 10 km distance from the EKA station location.
3. In cases where the turbine manufacturer is unknown, synthetic spectra representing turbine types likely to be used in the consultation zone in the future are assessed, and the highest value taken (i.e., an empirical worst-case),

The work presented here follows and builds upon the previous studies:

- Eskdalemuir Wind Turbine Seismic Vibration: Assessment of Headroom (SGV_201_Tech_Report_v04)
- Eskdalemuir Wind Turbine Seismic Vibration: Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning (SGV_202_Tech_Report_v07)(see Appendix E for summary)
- Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements (SGV_203_Tech_Report_v12)
- Phase 4: Field Audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions (SGV 204 Technical Report v12.pdf)
- Phase 5: Calculations to confirm maximum turbine seismic level to deploy minimum of 1GW deployment, (SGV-205-LimitSet-TechReport-v13)

3. Technical Background

Xi were commissioned by the Eskdalemuir Working Group (EWG) in 2013 to develop a robust physics-based approach to estimating the worst-case seismic ground vibration produced by wind turbines. Xi developed a predictive 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”* (2014).

The physics-based approach uses an algorithm that calculates a displacement power spectrum (Power Spectral Density; PSD) (frequency vs seismic ground vibration PSD) that represents the vertical component of seismic ground vibration measured at 1 km from any given turbine when the wind speed at a height of 80 m is 12 m/s. The premise behind the physics-based algorithm is that the wind energy that passes through a wind turbine can be considered to be portioned to electrical energy and lost energy. Losses will consist of energy converted to noise, frictional heat, seismic energy etc. Thus, some proportion of the energy passing through the rotor is converted to seismic ground vibration. The wind energy passing through the rotor is a function of wind speed and the swept area of the rotor. Thus, assuming that the proportion of wind energy that is lost to seismic ground vibration is constant, it is possible to scale the predicted seismic ground vibration based on blade length (to give swept area) and hub height (giving wind speed relative 12 m/s at a height of 80 m). The input requirements for the algorithm are therefore hub height and rotor diameter which are commonly submitted with a planning application making the algorithm viable for the purpose of predicting seismic ground vibration at the planning stage of a wind farm’s development.

The algorithm includes a FDWF, which accounts for the variation in transmission with distance over a range of frequencies, to account for the sensitivity to signals detected at the array. This function could be used to design distance-specific mitigation measures if required.

The algorithm variables were adjusted in order to best match or ‘fit’ the prediction with the measured seismic ground vibration data. The seismic ground vibration data used are from operational wind farms in southern Scotland available in 2012. These wind farms were Craig wind farm consisting of four Nordex N80 turbines with a hub height of 60 m and rotor diameter of 80 m; Clyde wind farm consisting of 152 Siemens 2.3 MW turbines (at the time of measurement) with a hub height of 78.3 m and rotor diameter of 93 m and Dun Law wind farm 26 Vestas V47 turbines with a hub height of 40 m and a rotor diameter of 47 m. As of 2023 these machines represent an older generation of wind turbine.

A key observation from the measurement of these three wind farms was that the seismic ground vibration spectra produced by wind farms either related to blade-pass (Craig and Dun Law), or structural resonances (Clyde). Due to the limited public data available on seismic emissions from wind turbines, a conservative ‘worst-case’ approach was adopted. This worst-case turbine algorithm assumes that any given turbine produces *both* forms of seismic ground vibration, i.e., blade-pass *and* structural resonance. Continuing this conservative approach, the algorithm includes a factor of safety by over-fitting the empirical data by ~20% to account for uncertainty in the seismic output of different makes and models of wind turbines.

“Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project” was reviewed by the MoD Subject matter expert (Dr D Bowers) who subsequently presented to the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and was ultimately accepted by the Scottish Government. Adopting the new algorithm opened up over 1GW of onshore wind power within the 50 km Eskdalemuir consultation zone compared to the MoD’s earlier safeguarding approach.

4. Summary of measurements

The seismic ground vibration at seven wind farms were measured between 30/04/2021 and 24/11/2021. Table 1 lists the make, model and dimensions of the turbines at each wind farm and the number of turbines. Table 1 also lists the turbines of previous measurements (conducted for the EWG and Scottish Government) at Clyde and Middle Muir wind farms. Based on *Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements* (SGV_203_Tech_Report_v12), all known manufacturers with turbines in the consultation zone with megawatt class turbines ($\geq 1\text{MW}$) have been measured.

Farm	OtherName	Manufacturer	Model	Number of Turbines	Hub Height	Rotor
Craig Hill	(Carlesgil and Extension)	Nordex	N80	4	60	80
		Enercon	E82	2	59	80
Glenkerie	(MiddleHill)	Vestas	V80	6	60	80
				5	78	80
Harestanes		Gamesa	G8x	67	78	87
				1	67	80
Langhope Rig		GE	GE 1.6	10	80	82.5
Minnygap		Nordex	N100	10	75	99.8
Solwaybank		Vestas	V100	15	76.5	100
Ewe Hill		Siemens	SWT2.3	23	63.3	93
Previous Measurements						
Clyde		Siemens	SWT2.3	152	78.3	93
Middle Muir		Senvion	3.4M114	7	92.9	114
				8	79	114

Table 1 Summary of the wind farms measured listing the models and the dimensions of the turbines

Full details of the measurement at each wind farm and the approach to post processing the data are detailed in Appendices D.1 to D.7. At each wind farm, Güralp 6TD medium-motion, three component, broadband seismometers were deployed at four locations to measure seismic ground vibration. Multiple sensors were deployed to cover sensor failure and variations in local site conditions. It is accepted practice that the sensor with highest signal-to-noise ratio (where the signal is ascribed to wind turbine generated ground vibration) be used to represent each site. Table 2 lists the sensor with the highest signal-to-noise ratio at each wind farm and data from these sensors are used in all subsequent calculations.

The seismic ground vibration recorded at each of the sensor locations listed in Table 2 were normalised to a single wind turbine for the given wind farm measured at a distance of 1 km following the normalisation process as described in Appendices D.1 to D.7 that is based on the method defined in “*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*” (2014).

The values of the PSD and topology of the seismic ground vibration spectra from the turbines measured at 12 m/s wind speed are broadly consistent with those previously measured at Craig, Clyde and Middle Muir wind farms (Figure 1 and Figure 2). Exceptions to this topological consistency in the measured data are those from Minnygap and Solwaybank (see below).

Wind Farm	Sensor with lowest background noise level
Craig Hill	SL3
Glenkerie	SL4
Harestanes	SL3
Langhope Rig	SL3
Minnycap	SL4
Solwaybank	SL3
Ewe Hill	SL3

Table 2 Sensor at each wind farm with the highest signal-to-noise ration. Data from these sensors are used to represent each wind farm in subsequent calculations

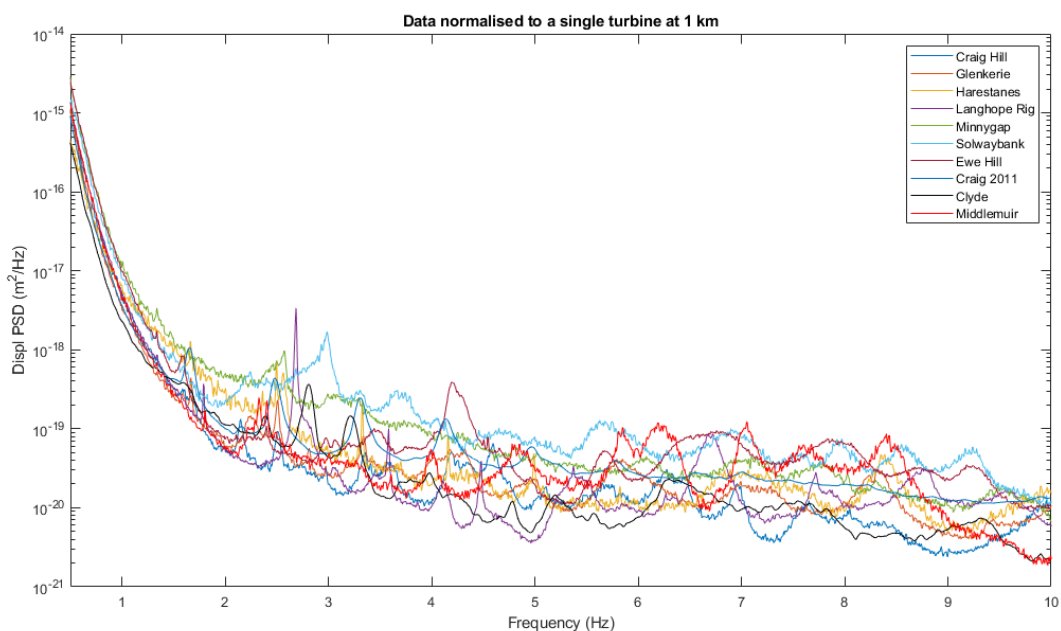


Figure 1 Vertical component of seismic ground vibration displacement PSD at each wind farm normalised to represent a single turbine measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

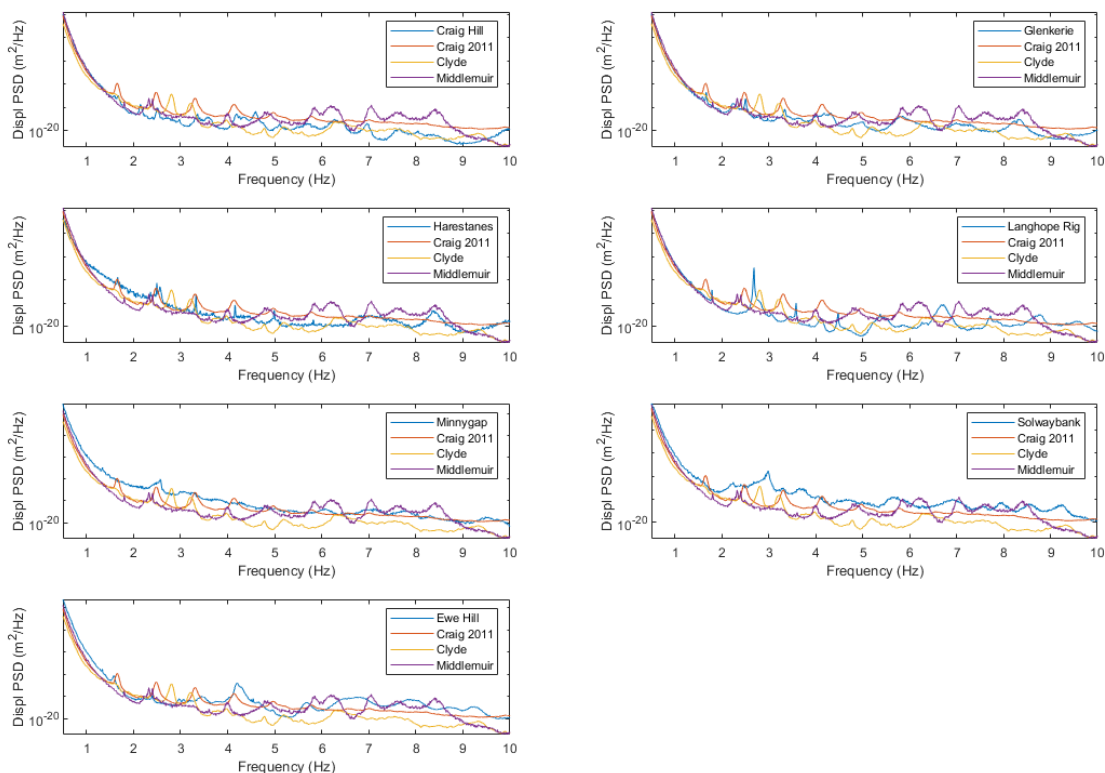


Figure 2 Vertical component of ground vibration displacement PSD at each wind farm measured in the 2021 campaign compared to previously measured sites. The spectra have been normalised to represent a single turbine measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m. The top (blue) line in the key is the new 2021 data compared to historic results, for example Craig Hill (top left) refers to the new data from Craig Wind Farm with four Nordex N80 turbines and two Enercon E82.

4.1. Background noise at Solwaybank and Minnygap

The seismic signal recorded at each temporarily deployed sensor includes background noise not generated by wind turbines. The background noise comes from natural sources or from localised human activities. A significant source of background noise is from wind interacting with the ground surface and other structures such as trees. The background noise increases with wind speed as these interactions become more vigorous. As the wind speed increases, the background noise level can mask seismic ground vibration generated by wind turbines. This has been a common observation in previous wind turbine field measurements and has confounded some surveys where it is not possible to detect wind turbine signals due to background noise induced by high winds in combination with other vibration sources.

At Minnygap peaks at 2.6 Hz and 3.3 Hz are visible in spectra measured up to wind speeds of 8 m/s (Figure 3). These peaks could be attributed to the Nordex N100 turbines at Minnygap, most likely due to structural resonances. However, at 12 m/s these signals are masked by the wind induced background noise such that seismic power measured at this wind speed is attributed mostly to sources other than from the wind turbines (Figure 3).

At Solwaybank peaks at 2.1 Hz, 2.9 Hz, 3.6 Hz and 4.3 Hz are noted in the spectra measured up to 8 m/s wind speed (Figure 4). These peaks can be attributed to seismic ground vibration generated by blade pass of the Vestas V100 turbines; in the case of the peak at 2.9 Hz, there is likely an interaction with a structural resonance resulting in a peak with significant power. Like Minnygap, these peaks are masked at higher wind speeds such that the majority of seismic power measured at 12 m/s wind speed is attributed to sources other than from the wind turbines (Figure 4).

Given that the 12 m/s spectra from Minnygap and Solwaybank do not reflect the seismic ground vibration produced by wind farms, these measurements are excluded from the budget calculations below. For clarity, the spectra are compared in Figure 5 with Minnygap and Solwaybank excluded.

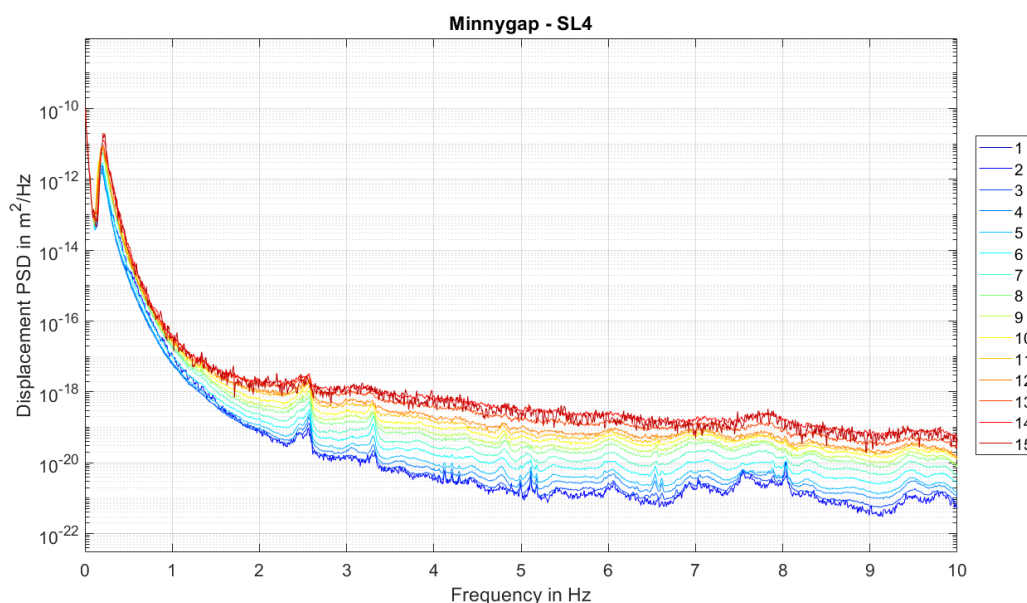


Figure 3 Variation of the vertical component of ground vibration in displacement PSD with wind speed in m/s at Minnygap measured at 75 m above ground level and extrapolated to the reference wind height of 80m.

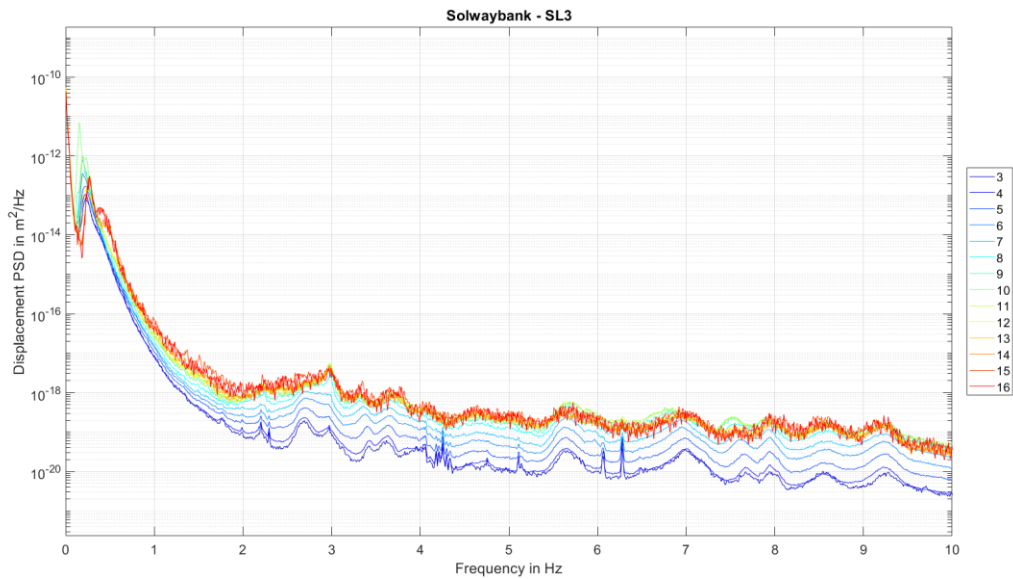


Figure 4 Variation of the vertical component of ground vibration in displacement PSD with wind speed in m/s at Solwaybank measured at 76.5 m above ground level and extrapolated to the reference wind height of 80m.

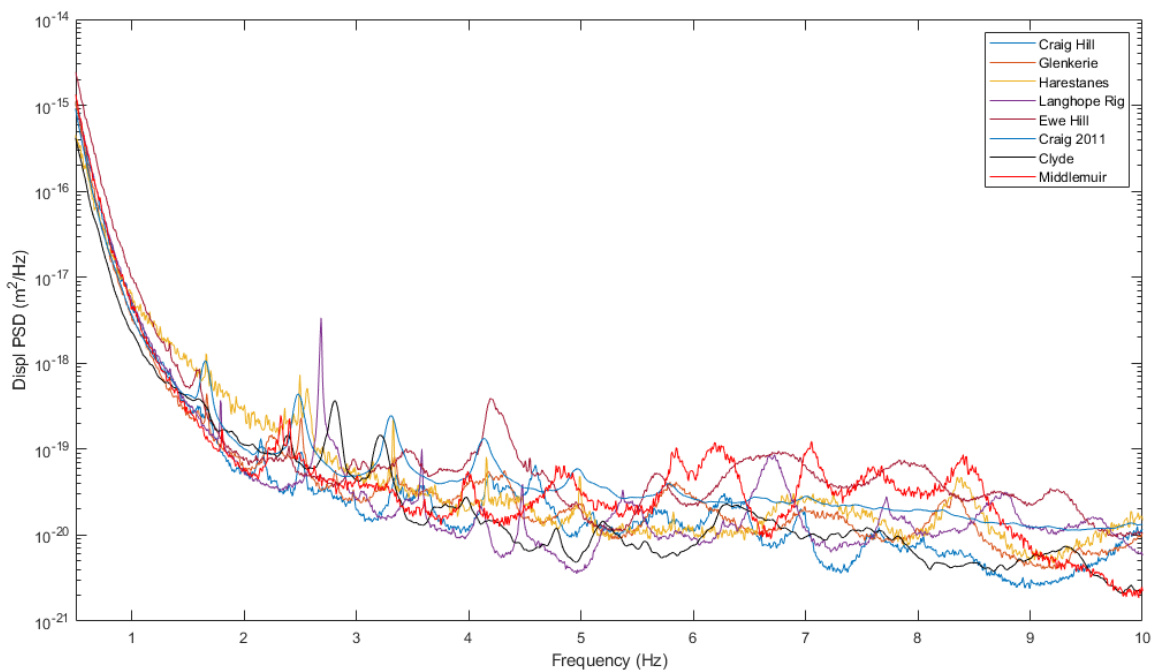


Figure 5 Seismic ground vibration displacement PSD at each wind farm with Minnygap and Solwaybank excluded. The data are normalised to represent single turbines measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

4.2. Background noise and extrapolation at Harestanes

The Harestanes measurement also had high levels of background noise due to ground conditions at the site. As noted in Appendix D.4 low wind speeds over the summer of 2021 resulted in no data being collected in the 12 m/s wind speed bin. The high site background noise and extrapolation (see Appendix D.4) resulted in unrealistically high broadband noise levels measured at Harestanes. Unlike Minnygap and Solwaybank, spectra peaks attributed to wind turbines can be discerned at 11 m/s wind speeds (Figure 6) and the data has been used in the budget calculations below. However, it should be noted that it is likely that the seismic ground vibration predicted for the Gamesa wind turbines installed at Harestanes are unrealistically high.

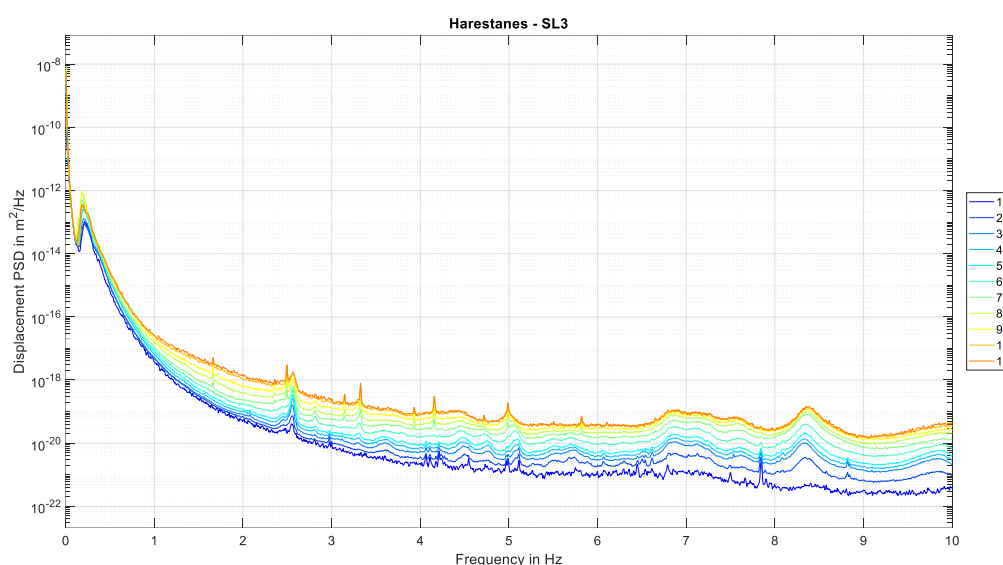


Figure 6 Variation of seismic displacement PSD with wind speed at Harestanes, wind speed measured in m/s at 80m

5. Measured data compared to algorithm estimates

The current algorithm used to calculate the EKA budget contributions uses a worst-case turbine to represent the spectra of any given wind turbine at a distance of 1 km (based on the turbine’s rotor diameter and hub height). This worst-case turbine spectrum can be replaced by processing data measured at wind farms that have turbines with the same make and model as those in the consultation zone. This approach considers that all seismic energy measured was seismic ground vibration generated by the given wind farm and is therefore an over-estimate as it includes background noise.

The impact of wind farms with makes and models that have been measured are listed in Table 3. The amplitudes consider the distance from EKA using the FDWF, which is consistent with the budget calculations. Table 3 also lists the impact as calculated by the budget using a worst-case turbine (see Budget Algorithm column in Table 3). As noted above, the values for Harestanes are unrealistically high and have been included in Table 3 for completeness. The measured values are all lower than those estimated by the current algorithm by between 24.1% and 42.7%. The cumulative measured impact for these wind turbines is 31.7% lower than estimated by the budget.

Wind Farm	Number Of Turbines	Manufacturer	Model	Measured (nm)	Budget Algorithm (nm)	Over-estimate
Carlesgill (Craig)	4	Nordex	N80	0.0223	0.0351	36.6%
	2	Enercon	E82			
Langhope Rig	10	GE	GE1_6	0.0306	0.0403	24.1%
Clyde	152	Siemens	SWT2_3	0.0499	0.074	32.5%
Ewe Hill	22	Siemens	SWT2_3	0.0602	0.0886	32.1%
Glenkerie	11	Vestas	V80	0.0115	0.0162	29.0%
Middle Muir	15	Senvion	M114	0.0036	0.0062	42.7%
Cumulative total				0.0877	0.1284	31.7%
Harestanes*	68	Gamesa	G8x	0.0662	0.0571	-15.9%

Table 3 Seismic impact of each wind farm based on measured data and considering the distance of each turbine from EKA using the FDWF curve. The estimate and the budget algorithm is also shown as is the Budget Algorithm over-estimate taken as the percentage that the budget level exceed the measured level. *The Harestanes measurement included significant background noise due to ground conditions and low wind speeds required extrapolation 12 m/s, the results shown here include unrealistically high broadband noise levels.

6. Extrapolation to entire budget list

Audits of the EKA budget list have been conducted a number of times during the Phase 1-Phase 5 work. Notably the EKA Budget spread sheet *20118 EKA Audited Tables Final V4- BASE.xlsx* that was generated during the budget audit phase of work and issued to the Scottish Government as part of “Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements (SGV_203_Tech_Report_v12)”.

The most recent audit was conducted initially by the Scottish Government and then by Xi Engineering Consultants, supported by AIFCL members. The Scottish Government conducted an audit of all sites within the EKA consultation zone listing the planning/consent reference and making any alterations as appropriate. The spreadsheet ‘EKA Audited Tables – Planning permissions vs built out-Aug2023.xls’ was issued by the Scottish Government on the 11th August 2023.

Xi Engineering Consultants conducted a secondary audit assessing latest planning documentation and cross-referencing data against the RenewableUK Energy Pulse system. Sites for which planning had expired, been refused, and had no further appeal process available were removed from the list.

This document solely deals with sites up to and including Scotston Bank Wind Farm as this was the last wind farm to receive MoD budget allocation. The budget list data is accurate as of the 28th August 2023.

The spreadsheet contains wind turbine models that have not been measured and cannot therefore be represented using directly measured data. Instead, data from specific manufacturers (makes) have been extrapolated to different models based on the rotor diameter and hub height (e.g., Nordex N80 extrapolated to represent a Nordex N133). To extrapolate the data, the method similar to that used in *Eskdalemuir Wind Turbine Seismic Vibration: Assessment of Headroom (SGV_201_Tech_Report_v04)* and *Eskdalemuir Wind Turbine Seismic Vibration: Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning (SGV_202_Tech_Report_v07)* is followed.

In *SGV_201_Tech_Report_v04* and *SGV_202_Tech_Report_v07* the algorithm used to represent wind turbines was tightly fitted to data from Craig, Clyde and Middle Muir wind farms. The coefficients used by the algorithm to represent wind turbines were adjusted and the algorithm iterated until a tight fit was achieved between data and algorithm. A similar approach was followed in the previous issue of this Phase 4 Report (*SGV 204 Technical Report v12.pdf*), where the coefficients are adjusted to fit the Craig data for Nordex and Enercon turbines, Langhope Rig for GE, Harestanes for Gamesa and Glenkerie for Vestas. In this issue, the measured spectra have again been fitted with the refinement of weighting the fitting using the FDWF appropriate for a distance of 10 km. Weighting the fit using the FDWF for 10 km means that spectra are best fitted for turbines at distances that are likely most impactful on EKA.

The algorithm used coefficients to represent seismic ground vibration PSD displacement spectra peaks related to blade pass and a single structural resonance. Here, three additional structural resonances have been included to better represent data from all wind farms. This is accomplished by adding three terms to equation 15 of *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*” (2014):

$$SynS_{(f,v_w,A,f_{BP})} = OBN_{(f,v_w)} + BM1_{(f,v_w,A)} + BM2_{(f,v_w,A)} + BM3_{(f,v_w,A)} + BM4_{(f,v_w,A)} + BP_{(f,v_w,A,f_{BP})}$$

where *SynS* is the synthetic seismic ground vibration PSD spectra used to represent the turbine, *OBN* is the operational broadband noise, *BM1* *BM2*, *BM3* and *BM4* are the four structural resonances (bending modes)

and BP are peaks relating to blade pass. The variable f is frequency, A swept rotor area and v_w is wind speed. The coefficients used to represent the turbines produced by each manufacturer are listed in Appendix A with figures showing the fitting in Appendix B. The fit of the synthetic spectra to measured data normalised to a single turbine for each wind farm, weighted using the FDWF appropriate for 10 km distance, is listed in Table 4. Figure 7 shows an example of the synthetic spectrum fitting for Glenkerie (Vestas) which is based on the turbine being a distance of 10 km from EKA.

The coefficient of determination values (R^2 value) for the fit of the synthetic spectra to the measurements are generally very high (>0.80). Middle Muir has a slightly low R^2 value which may be due to the presence of seismic signal from the neighbouring Andershaw wind farm which is not accounted for in the synthetic spectrum. The Harestanes fit also has a slightly low R^2 value which is likely due poor signal to noise ratios in the measured data due to the high background noise levels from numerous sources (see Section 4.2). The amplitudes of measured and modelled spectra for the given turbines weighted using the FDWF appropriate for 10 km are also listed in Table 4, which shows there is good agreement between the measured data and the modelled synthetic spectra.

Wind Farm	R^2 Value	Measured Amp (nm)	Modelled Amp (nm)
Clyde	0.858	0.04398	0.04398
Craig 2011	0.951	0.06427	0.06427
Middle Muir	0.730	0.05074	0.05074
Glenkerie	0.924	0.04628	0.04628
Harestanes	0.755	0.06393	0.06393
Langhope Rig	0.817	0.04446	0.04446
Minnygap	0.940	0.08532	0.08532
Solwaybank	0.904	0.10854	0.10854
Ewe Hill	0.938	0.07135	0.07135
Craig (Nordex & Enercon)*	0.901	0.04121	0.04125

Table 4 Fitness of synthetic spectra for each wind farm with measured results. The R^2 values are the coefficient of determination showing the proportion of variance between the prediction (model) and the measured data (a value of one would be a perfect fit). The measured and modelled amplitudes compare impact of placing the given turbine at 10 km from EKA. *In the case of Craig wind farm the fit taken as the summed ratio of turbines at 10 km, i.e., 4/6 Nordex N80 + 2/6 Enercon E82.

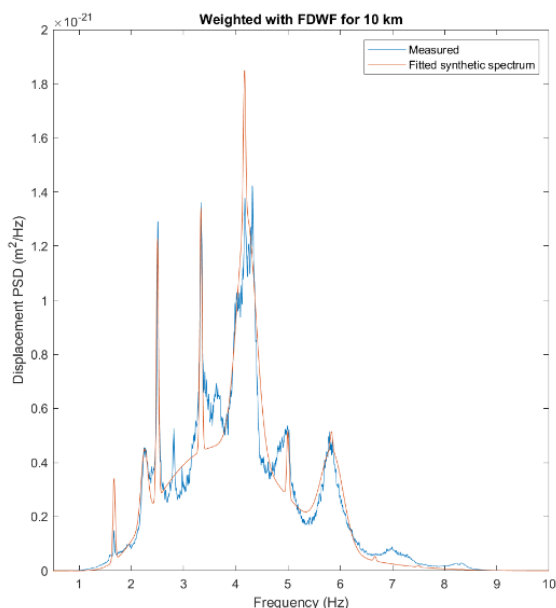


Figure 7 Example of fitting of synthetic spectra weighted for 10 km from EKA. The Glenkerie data representing a single turbine has been weighted using the FDWF appropriate for 10 km from EKA. The synthetic spectrum has been fitted so it best represents this turbine when it is most impactful on EKA, i.e., when it is closest to EKA.

6.1.1. Two manufacturers at Craig wind farm

Craig Wind Farm now contains both Nordex and Enercon turbines. Craig Wind Farm was measured in 2011 with results presented in *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project* (2014). In 2011 the wind farm contained only the four Nordex N80 turbines. The 2011 data was compared to data collected here to allow spectra peaks from the Nordex N80 to be discriminated from those related to the Enercon E82 turbines (Figure 8). The measured operational broadband noise is lower in the 2021 measurement likely due to a combination of improved sensor installation techniques developed over the subsequent decade, lower level of ambient background noise at the time of the new measurement and the mature wind farm having less activity related to installation and servicing than was the case when the then new wind farm was measured in 2011.

Once the spectral peaks related to the N80 and E82 turbines were discriminated from each other the normalised spectrum was used to fit coefficients to represent relevant turbine makes. To fit for each make, the PSD of the normalised spectrum was adjusted to account for the number of turbines (i.e., 4 x Nordex N80 and 2 x Enercon E82). The fitting process assumes the operational broadband noise/background noise is produced by both the N80 turbines and the E82 turbines; this background noise is therefore double counted resulting in a slightly higher spectrum representing the N80 and/or the E82. However, given that there is no way to discriminate the amount of broadband noise contributed by either turbine make, a conservative approach is followed here, and the double counted values used.

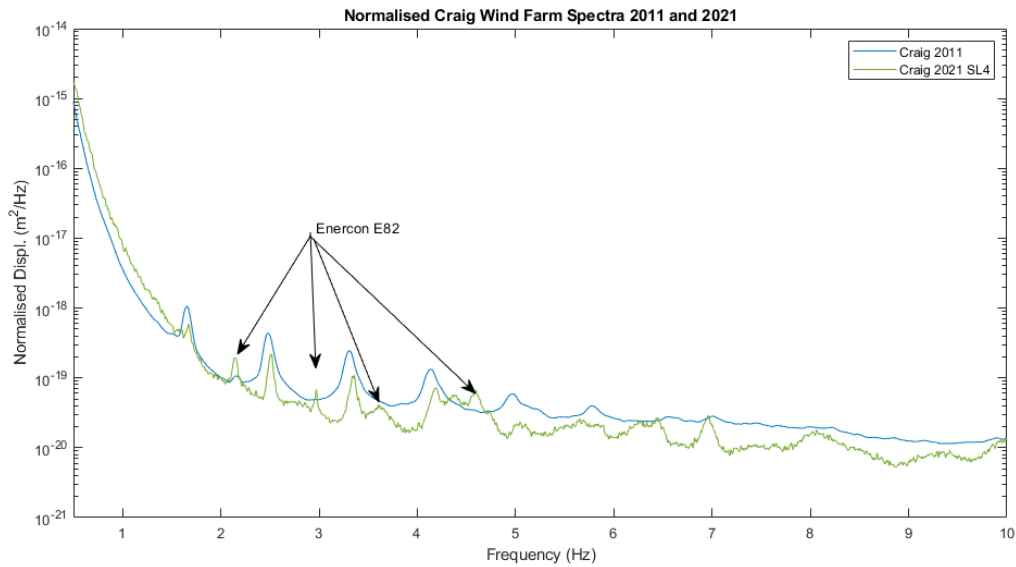


Figure 8 Comparison of data measured at Craig wind farm in 2011 when four Nordex N80 turbines were present compared to 2021 when the wind farm has an additional two Enercon E82 turbines.

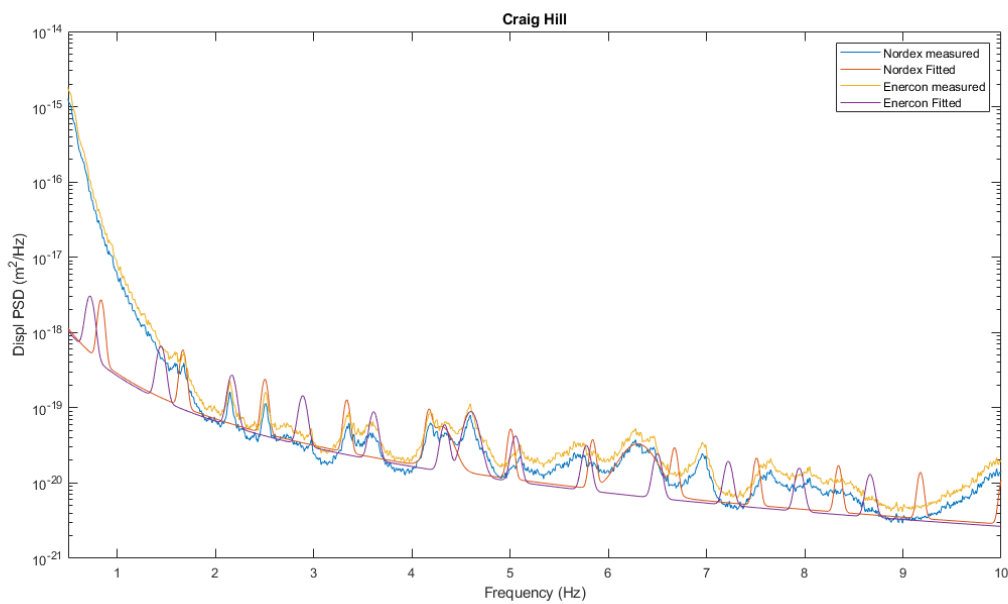


Figure 9 Result of fitting the spectra to account for Nordex and Enercon turbines. The initial normalisation to a single turbine at 1 km was based on six turbines at Craig wind farm. The measured spectrum has been adjusted to account for there being two Enercon turbines and four Nordex, so that spectral peaks used for fitting have the correct amplitude.

6.1.2. Two hub heights at Glenkerie

The Glenkerie Wind Farm consists of eleven Vestas V80 wind turbines, of which six have hub heights of 60 m, and five have a hub heights of 78 m. Following a conservative approach, the coefficients were fitted such that it assumes that spectral peaks are produced by turbines with a 60 m hub height (see Appendix B).

6.1.3. Unknown and unmeasured turbines

Many wind farms in the budget list are at the planning stage and have yet to determine which wind turbine make and model will be installed at the proposed farm. Further, the single wind turbine sub-MW (500 kW) turbine listed as West of M6 Todhill was an operational EWT wind turbine for which there is no measured data. The unknown turbines at proposed wind farms require a fitted spectra to estimate their seismic ground vibration contribution. In cases where the wind turbine is listed as unknown or EWT, the seismic ground vibration predicted by each of the synthetic spectra for the turbines assessed (see Appendices A and B), except for Harestanes (Gamesa) and Middle Muir (Senvion), is calculated and the highest value taken; this can be considered a conservative empirical worse-case approach. Gamesa and Senvion turbines are no longer in production and so they were not considered as viable turbines for future use in the consultation zone (The Senvion machine is an addition to the no longer in production approach used in the previous v12 issue of this Phase 4 Report (*SGV 204 Technical Report v12.pdf*)).

6.1.4. Budget list assumptions

In order to accurately calculate the numerical budget position, the budget list was assessed to cleanse and update it up to the 28th August 2023. The following actions were taken during this process:

- Full audit of all sites and planning status
- Cross reference with Planning Data and RenewableUK Energy Pulse system conducted
- All sites that have been withdrawn or refused with no option for appeal were removed
- Constructed sites as of 28th of August 2023, have been allocated budget using phase 4 results based on as built turbine manufacturer and turbine locations
- Sites with planning permission and existing conditions or legal agreements with MoD have been allocated standard EKA budget
- All the sites within the Eskdalemuir region which have entered the planning system have now been included

To be consistent with the previous head-room calculation (Phase 5 Report, *SGV-205-LimitSet-TechReport-v13*) the budget was calculated up to and including Scotston Bank Wind Farm. Scotston Bank Wind Farm was the last site to not receive an MoD objection on grounds that the budget limit has been exceeded.

6.2.Results

All sites which did not receive an objection from the MoD on budget threshold grounds have been included within the calculations. Based on the set of assumptions detailed here, the cumulative seismic impact of all wind farms in the budget list up to and including Scotston Bank is 0.20756 nm. This is substantially below the budget threshold of 0.336 nm. Given that the impact of wind farms adds in quadrature, the head-room is 0.26422 nm:

$$\sqrt{0.336^2 - 0.20756^2} = 0.26422$$

	Cumulative budget (nm)	Head room (nm)
Budget up to and including Scotston Bank Wind Farm	0.20756	0.26422

7. Discussion

7.1.Uncertainties and assumptions

Measured data has been used here to better calculate the seismic ground vibration contribution of wind turbines in the consultation zone. The seismic ground vibration predicted from a single wind turbine in the current budget algorithm was fitted to a relatively small dataset of just three wind farms that was available in 2014. Given the initially small dataset used to fit the algorithm in 2014, a safety factor was applied to ensure that the detection capabilities of EKA were not placed at risk. The data presented here show that the current budget algorithm has not under-estimated the contribution of any wind farms measured and that the cumulative amplitude from installed and operating wind turbines has not endangered the capabilities of EKA.

The data presented here was used to calculate the actual installed capacity rather than estimated. However, it is not viable to retrospectively measure every wind turbine in the Eskdalemuir consultation zone, so a degree of extrapolation of data is required. In cases where decisions regarding data handling and extrapolation were required, a conservative worst-case approach was taken that was consistent with previous work. The following assumptions used in the previous v12 of this Phase 4 Report (*SGV 204 Technical Report v12.pdf*) were again employed here:

- A worst-case approach was taken for separating the Nordex and Enercon turbines in that the broadband noise/background noise was effectively double counted.
- The worst-case approach was also taken when fitting data to the Glenkerie Wind Farm to represent Vestas turbines, whereby the smallest of the hub heights was used.

In cases where the wind turbine manufacturer for a given wind farm was 'unknown' or EWT, the synthetic spectra for all wind turbines for the distance from EKA, hub height and rotor diameter were assessed, and the highest amplitude taken; again following an empirical worst-case approach. This methodology varies from the previous v12 Phase 4 work where a GE turbine based on Langhope Rig was used for 'unknown' and EWT turbines.

High background noise levels were measured at Minnygap and Solwaybank at 12 m/s such that the spectra do not reflect the ground vibration produced by wind farms and these measurements were excluded from the budget calculations below. The impact of Minnygap and Solwaybank on EKA was calculated using the fitted

data for Nordex and Vestas machines respectively scaled for the given turbine rotor diameters and hub heights. Following the assumptions above, this scaling does not underestimate Minnygap and Solwaybank's impact on EKA.

Due to low wind speeds over the summer of 2021 no data was recorded at Harestanes in the 12 m/s wind speed bin and data had to be extrapolated from lower wind speed bins to produce a 12 m/s spectrum. This process resulted in the broadband noise/background noise also being extrapolated to unrealistically high levels. The extrapolated 12 m/s wind speed bin was used to fit the coefficients that represent Gamesa turbines and, therefore, likely over-estimate the operational broadband noise level. Furthermore, Harestanes had notably high background noise levels due to ground conditions (see Appendix D4). In previous studies such as "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014), high background noise levels at Craig Wind Farm were overcome by applying the operational broadband noise coefficient measured elsewhere. This approach could be followed to model the Gamesa turbine here. However, following a conservative approach, the contribution from Gamesa turbines was modelled using the operational broadband noise as measured and extrapolated from the Harestanes data. This is consistent with work presented in the previous version (v12) of this Phase 4 Report (*SGV 204 Technical Report v12*) and Phase 5 Report, (*SGV-205-LimitSet-TechReport-v13*)

7.2. Implications for head room and further capacity

The conversion of budget head room to additional wind energy capacity is detailed in the accompanying report AIFCL-101-Phase5-Rev-v11.

7.3. Implication of exclusion zone

The effect of changing the radius of the exclusion zone on additional wind energy capacity is detailed in the accompanying report AIFCL-101-Phase5-Rev-v11.

7.4. Background noise levels

The measured data reported here and from previous reports include background noise which is not generated by wind turbines. The background noise comes from natural sources or from localised human activities. As all wind farm sites were not measured prior to installation; without pre-installation seismic data, background noise caused by non-turbine sources is not accurately able to be removed. Removing the background seismic energy to calculate the contribution of just wind turbine seismic ground vibration would provide an additional increase in the available budget headroom and thus increase deployment within the region. Available data shows that the seismic energy produced by the wind turbine increases with the cube of the wind speed, as would be expected as the energy content of the wind varies with the cube (the third power) of the average wind speed. However, the background noise can increase at a greater rate than the third power which results in background masking the turbine signals at higher wind speeds. Conducting before and after installation measurements of sufficient length could allow quantification of background noise and provide a means of removing this energy from the calculations. Increased understanding of how the background noise scales at sites would potentially allow future measurements to be simplified and clarify methodology for background noise removal. Removal of background noise could effectively reduce the seismic levels of the turbines and further increase capacity in the region, while continuing to rigorously protect the EKA.

8. Conclusion

Data was collected at seven wind farms and was combined with those from previous measurements which allowed an assessment of the seismic ground vibration contribution from wind turbines to background seismic noise at EKA (this report supersedes Phase 4 Report, SGV 204 Technical Report v12.pdf). These data were used to determine coefficients that describe synthetic seismic ground vibration spectra representative of different turbine types commonly constructed in the Eskdalemuir consultation zone. The spectral fitting was weighted to best represent turbines 10 km from the EKA using an appropriate frequency-distance weighting curve. In the event that turbine manufacturers for given wind farms were unknown five synthetic spectra, representing turbine types likely to be used in the consultation zone in the future, were assessed, and the highest predicted seismic ground vibration used. Based on these worst-case assumptions the cumulative amplitude of all turbines up to and including Scotston Bank is 0.20756nm, significantly below the 0.336 EKA threshold. The head-room based on these calculations is 0.26422 nm.



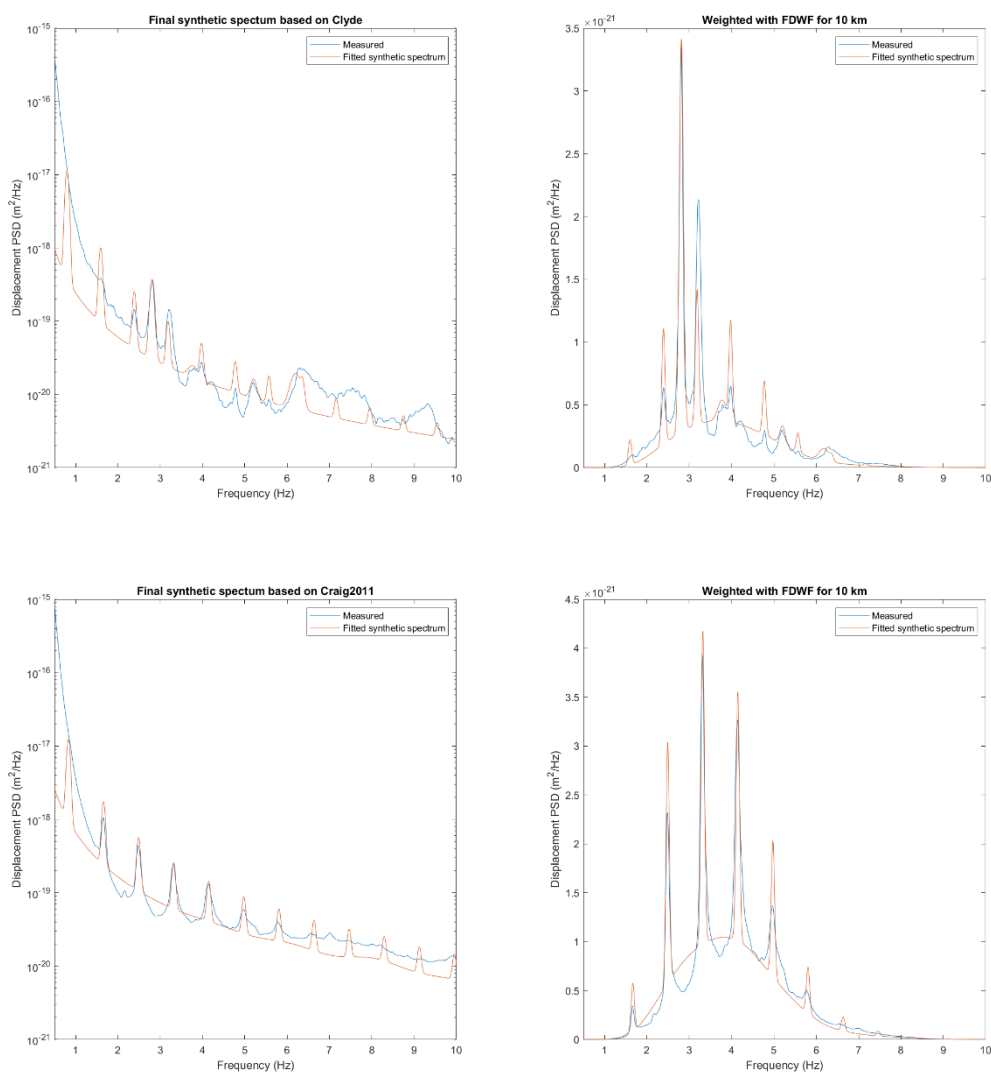
9. Appendix A – Coefficients used to represent turbines by manufacturers.

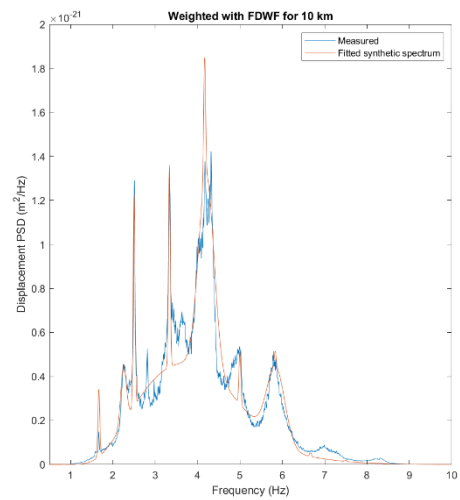
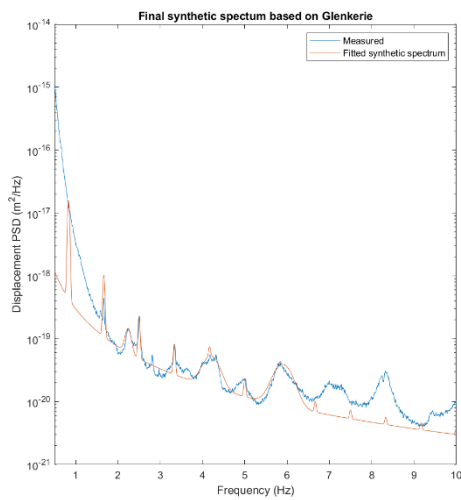
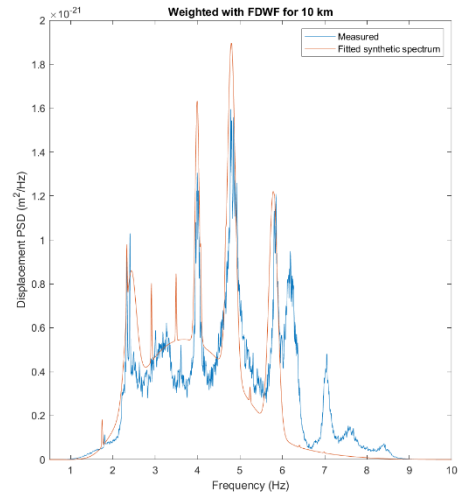
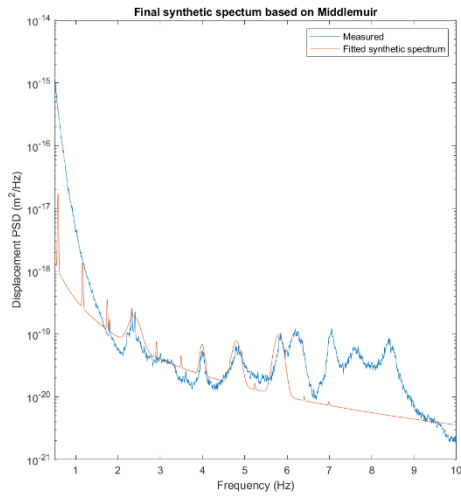
Turbine Manufacturer	Standard EKA	Siemens	Senvion	Vestas	GE	Nordex	Enercon	Gamesa
Wind Farm Fitted	2014_worstcase	Clyde	Middle Muir	Glenkerie	Langhope Rig	Craig Nordex	Craig Enercon	Harestanes
Blade pass amplitude multiplier	2.8739E-25	4.1651E-25	1.1050E-25	9.3387E-25	9.8920E-25	1.7138E-25	1.6000E-26	7.3806E-24
Blade pass amplitude exponent	1.76	3.6	3.85	4.05	3.036	3.2175	1.35	4.62
Blade pass shape parameter	0.04	0.04	0.01	0.022	0.006	0.0319	0.044	0.007
Bending mode 1 amplitude multiplier	9.2303E-26	2.9155E-26	6.7131E-27	1.1096E-26	3.5547E-25	1.0000E-26	3.0000E-30	5.0134E-26
Frequency of bending mode 1	2.808	2.81	2.39	2.24	2.68	2.1	2.96	2.57
Bending mode 1 shape parameter	0.05	0.05	0.13	0.066	0.011	0.044	0.55	0.039
Bending mode 2 amplitude multiplier	0.0000E+00	6.6890E-28	3.3151E-27	4.6531E-27	1.5445E-27	5.0000E-27	5.0000E-27	1.1486E-27
Frequency of bending mode 2	2.808	3.77	4.8	4.2	4.1	4.2	4.6	4.4
Bending mode 2 shape parameter	0.05	0.101	0.093	0.185	0.044	0.0385	0.1111	0.078
Bending mode 3 amplitude multiplier	0.0000E+00	6.2431E-28	2.4863E-27	3.9372E-27	2.8193E-27	5.0000E-27	1.4000E-27	2.3775E-27
Frequency of bending mode 3	2.808	5.2066	3.99	5.9	5.4	6.3	5.66	7.04
Bending mode 3 shape parameter	0.05	0.064	0.047	0.216	0.136	0.1045	0.2475	0.292
Bending mode 4 amplitude multiplier	0.0000E+00	1.1148E-27	4.6964E-27	3.2539E-30	1.1032E-26	6.2865E-28	1.4000E-27	3.4457E-30
Frequency of bending mode 4	2.808	6.2	5.8	7.1	6.7	8	7	8.3
Bending mode 4 shape parameter	0.05	0.117	0.102	0.5	0.078	0.099	0.1056	0.5
Operational broadband noise multipliers	2.2282E-26	2.0866E-26	1.9082E-26	3.8887E-26	1.9692E-26	2.2208E-26	2.2208E-26	7.3909E-26
Tip Speed (m/s)	77.49	77.49	69.5	69.8	77.49	69.9	60.5	75.9

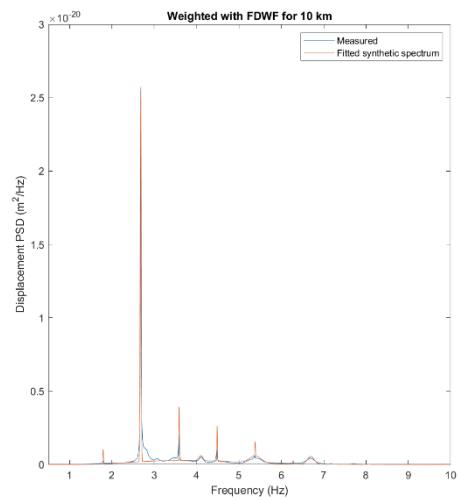
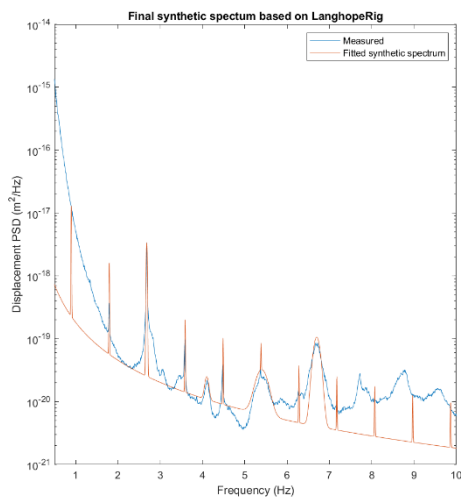
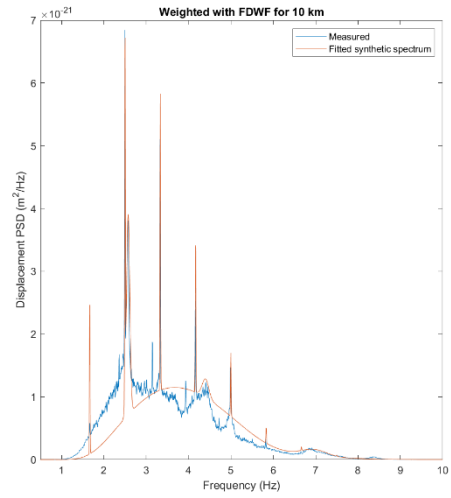
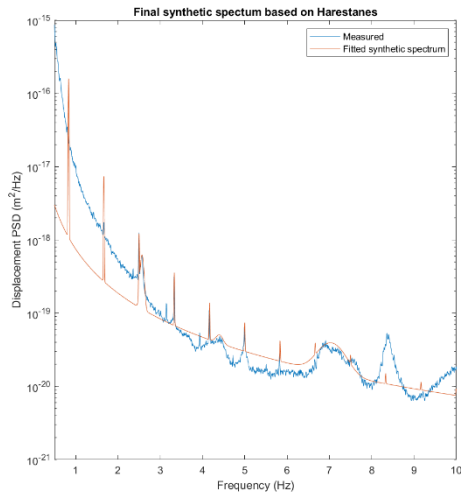
Coefficients used in the representations of seismic ground vibration output of wind turbines manufacturers. The wind farm data with which each set of coefficients were fitted are shown. The coefficients relate to those described in Section 8.2.1 of *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project* with parameters representing three additional bending modes. The Standard EKA coefficients are those currently used by the budget algorithm and include a factor of safety.

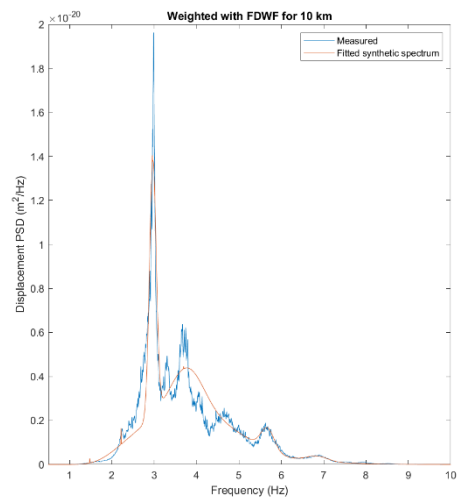
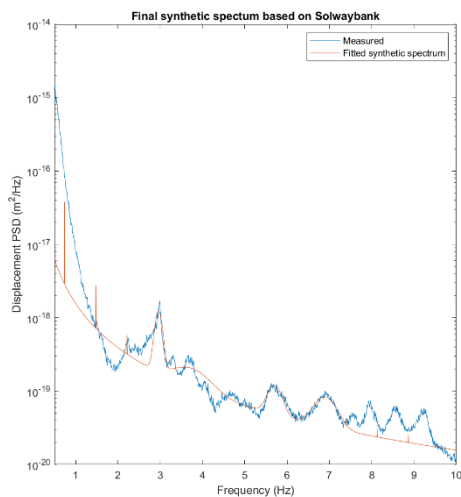
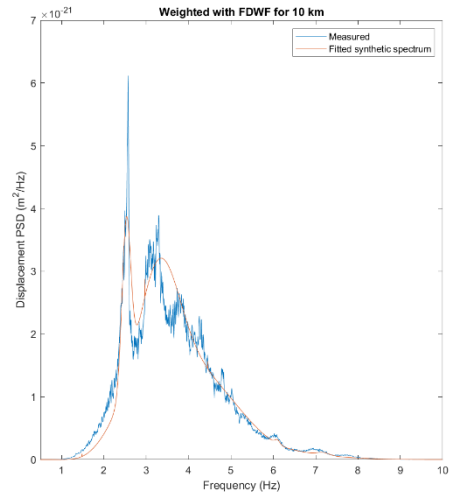
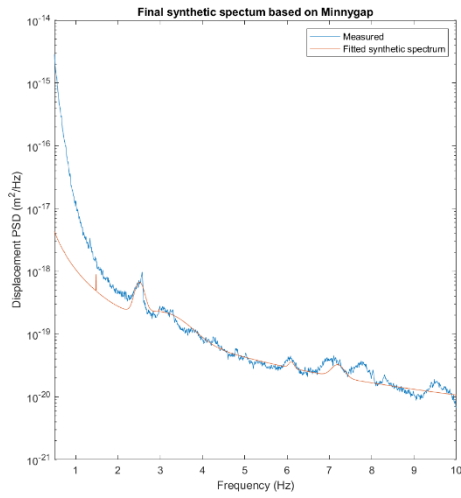
10. Appendix B – Fitting of Synthetic Spectra to measurement at each wind farm

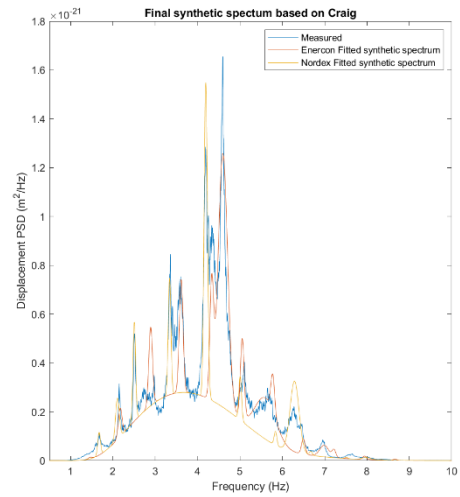
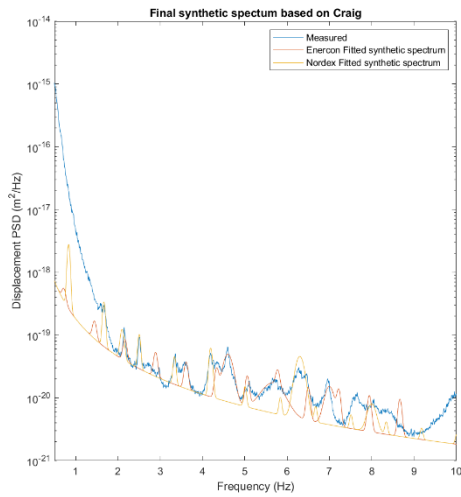
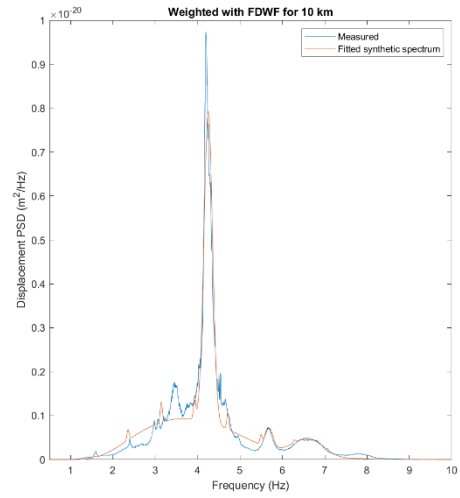
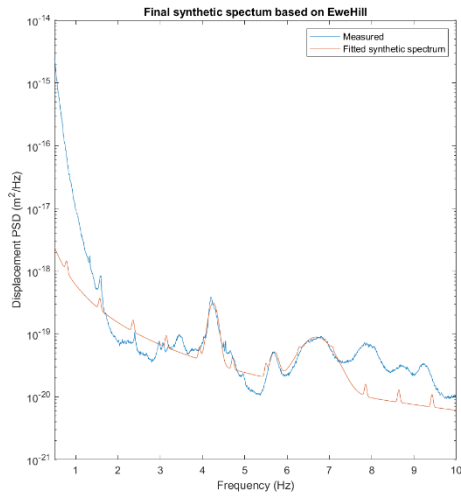
The coefficients used for the synthetic spectra are listed in Appendix A. The left-side of each figure compares the measured and fitted synthetic spectra normalised to single turbines at 1 km with no weighting, the right-side shows the comparison with a FDFW weighting appropriate for 10 km.











11. Appendix C Assessment of budget list

Wind Farm	Number of Turbines	Capacity (MW)	Manufacturer	Synthetic Spectrum Modelled	Amplitude of wind farm (nm)	Cumulative Amplitude of wind farms (nm)
Bowbeat	24	31.2	Nordex	Nordex	0.002605	0.002605
Carlesgill	4	10	Nordex	Nordex	0.014507	0.014739
Halkburn - Longpark	19	38	Senvion	Senvion	0.002973	0.015036
Langhope Rig	10	15	GE	GE	0.029959	0.033520
Clyde	152	456	Siemens	Siemens	0.047451	0.058096
Harestanes	68	204	Gamesa	Gamesa	0.055913	0.080631
Dalswinton	15	30	Senvion	Senvion	0.005296	0.080805
Minsca	16	40	Siemens	Siemens	0.021790	0.083691
Carcant	3	9.9	Siemens	Siemens	0.000576	0.083693
Ewe Hill	22	50.6	Siemens	Siemens	0.055977	0.100688
Andershaw	11	36.3	Vestas	Vestas	0.003854	0.100762
Middle Hill - Glenkerie	11	22	Vestas	Vestas	0.011923	0.101464
Langshaw Farm	1	0.05	unknown	GE	0.000171	0.101465
Aikrigg Cottage	1	0.006	unknown	GE	0.000021	0.101465
Kingstown Ind Estate	1	0.015	unknown	GE	0.000030	0.101465
Lammerlaw Farm 7153	1	0.011	unknown	GE	0.000100	0.101465
Brunstock Close	1	0.006	unknown	GE	0.000020	0.101465
Minnycap	10	20	Nordex	Nordex	0.016537	0.102804
Carlesgill Ext	2	6.4	Enercon	Enercon	0.012319	0.103539
Land East of Braidwood	1	0.006	unknown	GE	0.000102	0.103539
Westmill Farm	1	0.11	unknown	GE	0.000069	0.103539
Windyknowe	1	0.006	unknown	GE	0.000043	0.103539
Land NW of Ferniehaugh	2	0.06	unknown	GE	0.000070	0.103539
Lochmailing	1	0.015	unknown	GE	0.000110	0.103539
Threepwood	1	0.015	unknown	GE	0.000077	0.103539
Rennieston Edge	1	0.06	unknown	GE	0.000049	0.103539
Meadowside Cottage	1	0.02	unknown	GE	0.000102	0.103539
Mosshouses Farm	1	0.015	unknown	GE	0.000072	0.103539
Land SW of Larkhill	1	0.015	unknown	GE	0.000073	0.103539
Hall Burn	6	18	Vestas	Vestas	0.004150	0.103622
Muirlea Farm	2	0.04	unknown	GE	0.000160	0.103623
Whinney Rig	1	0.1	unknown	GE	0.000376	0.103623
Hillfield	1	0.005	unknown	GE	0.000027	0.103623
Cargo Farm Cottage	2	0.04	unknown	GE	0.000111	0.103623
Land NW of The Batts	1	0.015	unknown	GE	0.000060	0.103623
Burnhouse	1	0.015	unknown	GE	0.000069	0.103623

Wind Farm	Number of Turbines	Capacity (MW)	Manufacturer	Synthetic Spectrum Modelled	Amplitude of wind farm (nm)	Cumulative Amplitude of wind farms (nm)
The Beeches	1	0.02	unknown	GE	0.000088	0.103623
Symington Mains Farm	1	0.02	unknown	GE	0.000086	0.103623
Midhill	1	0.015	unknown	GE	0.000107	0.103623
Newton of Wiston	1	0.015	unknown	GE	0.000072	0.103624
Newtonhead	1	0.06	unknown	GE	0.000130	0.103624
Gaups Mill	1	0.01	unknown	GE	0.000034	0.103624
South Melbourne Farm	1	0.006	unknown	GE	0.000045	0.103624
Walston Braehead Farm	3	0.18	unknown	GE	0.000160	0.103624
Easton Farm	1	0.02	unknown	GE	0.000075	0.103624
Pumro Fell	1	0.0015	unknown	GE	0.000056	0.103624
Rivox	1	0.015	unknown	GE	0.000503	0.103625
Braco Farm	2	0.06	unknown	GE	0.000075	0.103625
Land at Arthurshiels	1	0.02	unknown	GE	0.000098	0.103625
Hyndshawland	1	0.02	unknown	GE	0.000109	0.103625
Clyde Extension	54	162	Siemens	Siemens	0.030890	0.108131
East Millrig	1	0.015	unknown	GE	0.000132	0.108131
Solwaybank	15	30	Vestas	Vestas	0.026908	0.111429
Mallshill	1	0.005	unknown	GE	0.000067	0.111429
Middle Muir	15	51	Senvion	Senvion	0.003149	0.111473
Brockhouse	1	0.011	unknown	GE	0.000072	0.111473
Broomhills	1	0.01	unknown	GE	0.000074	0.111473
Land SW of Copland Farm	1	0.011	unknown	GE	0.000127	0.111474
Land N of Midtown Farm	1	0.05	unknown	GE	0.000114	0.111474
Birkenside Farmhouse	1	0.05	unknown	GE	0.000110	0.111474
Libberton Mains Farm	1	0.02	unknown	GE	0.000080	0.111474
Bankhouse	1	0.012	unknown	GE	0.000048	0.111474
Lammerlaw	2	0.044	unknown	GE	0.000137	0.111474
Cormiston Farm	1	0.02	unknown	GE	0.000133	0.111474
Hartsop	1	0.015	unknown	GE	0.000111	0.111474
Parkhouse Farm	2	0.04	unknown	GE	0.000120	0.111474
Shankfield Head	2	0.04	unknown	GE	0.000116	0.111474
Cambwell	1	0.011	unknown	GE	0.000150	0.111474
South of Hyndfordwells	3	0.18	unknown	GE	0.000162	0.111474
Rose Cottage	1	0.006	unknown	GE	0.000038	0.111474
Hillend Farm	1	0.011	unknown	GE	0.000153	0.111474
Glenkerie Extension	6	15	Senvion	Senvion	0.005815	0.111626
Deanfoot Farmhouse	1	0.05	unknown	GE	0.000103	0.111626
Lion Hill	4	9.2	Vestas	Vestas	0.010426	0.112112
West of Hyndfordwells Farm	1	0.02	unknown	GE	0.000066	0.112112
Crookedstane Farm	4	9.2	Vestas	Vestas	0.008415	0.112427

Wind Farm	Number of Turbines	Capacity (MW)	Manufacturer	Synthetic Spectrum Modelled	Amplitude of wind farm (nm)	Cumulative Amplitude of wind farms (nm)
Windy Edge	9	29.1	StandardEKA	StandardEK A	0.051891	0.123825
Blackdyke	1	0.01	unknown	GE	0.000054	0.123825
Cottage Farmhouse	1	0.011	unknown	GE	0.000063	0.123825
Lampits Farm 2	1	0.25	unknown	Vestas	0.000182	0.123825
Land NW of West Morriston Farm	1	0.05	unknown	GE	0.000136	0.123825
Solway re-sub (Beckburn)	9	31.05	Vestas	Vestas	0.005975	0.123969
Land East of Mossbank	2	0.022	unknown	GE	0.000159	0.123969
Twentysilling Hill	9	27	Vestas	Vestas	0.002050	0.123986
Townfoot	1	0.01	unknown	GE	0.000103	0.123986
South Slipperfield Farmhouse	1	0.05	unknown	GE	0.000108	0.123986
Rose Cottage (9812)	1	0.006	unknown	GE	0.000038	0.123986
Whitelaw Brae	14	50.4	StandardEKA	StandardEK A	0.048980	0.133310
East of Newton of Covington	2	0.04	unknown	GE	0.000115	0.133310
Bailey Town Farm	1	0.01	unknown	GE	0.000175	0.133310
Kilravoch	1	0.0012	unknown	GE	0.000022	0.133310
South Melbourne Farm 2	1	0.011	unknown	GE	0.000113	0.133310
SW of Kettlehill Farmhouse	1	0.012	unknown	GE	0.000037	0.133310
West of M6 Todhills	1	0.5	EWT	GE	0.000528	0.133311
Trough Head Farm	2	0.02	unknown	GE	0.000283	0.133312
72 Carlisle Road	2	0.17	unknown	GE	0.000289	0.133312
Clackmae Farm	1	0.1	unknown	GE	0.000180	0.133312
East of Whitslaid Farm	2	0.05	unknown	GE	0.000092	0.133312
Crossdykes	10	48	Nordex	Nordex	0.072011	0.151518
Whins Farm	1	0.085	unknown	GE	0.000574	0.151519
Loganhead	8	25.6	StandardEKA	StandardEK A	0.080086	0.171382
Jockstown Farm	1	0.1	unknown	GE	0.000523	0.171383
Burnswark Garage	1	0.5	unknown	GE	0.000723	0.171385
Hopsrig	12	42	StandardEKA	StandardEK A	0.112423	0.204967
Pines Burn	12	39.6	StandardEKA	StandardEK A	0.031084	0.207311
Priestgill	7	22.4	StandardEKA	StandardEK A	0.010145	0.207559
Land SE of Scotston Bank Farm	3	0.045	unknown	GE	0.000164	0.207559

12. Appendices D.1-D.7 – Measurement Reports for each Wind Farm

For full details of the measurement at each wind farm and the approach to post processing the data please see attached supplementary documents: Appendices D.1 to D.7, these have been updated with a minor amendment in line with this (2023) revision.

Appendix D.1 – Craig Hill

Appendix D.2 – Ewe Hill

Appendix D.3 - Glenkerie

Appendix D.4 - Harestanes

Appendix D.5 – Langhope Rig

Appendix D.6 - Minnygap

Appendix D.7 - Solwaybank

13. Appendix E – Summary of Results from Phase 2

The following text summarises the results of Phase 2 detailed in *SGV_202_Tech_Report_v07.pdf*:

The amount of additional wind energy capacity that the head-room may allow assuming an even spread of turbines through the consultation zone are listed in Table 5. The additional capacity and number of turbines listed in Table 5 are taken as the mean of 1000 simulations and the uncertainty is taken as one standard deviation. The additional capacity is dependent on the available head room, which in turn is dependent on the type of turbine used to calculate the head room. If the Senvion turbines at Middle Muir are representative of all turbines in the consultation zone resulting in head room of 0.097 nm, then 476±142 MW of additional capacity would likely result from the even distribution of ~141 3.4 MW turbines. Should the Siemens turbines at Clyde be representative then an additional 1.1±0.18 GW is likely and if the Nordex turbines at Craig are representative then the additional capacity would likely be 310±92 MW.

The additional number of turbines and related capacity is strongly dependent on the distribution of those turbines. Table 6 lists how the head room converts to additional capacity when more turbines are built close to 50 km, while Table 7 lists how the head room converts to additional capacity when more turbines are placed close to 10 km. For the given weighting in the distribution there is a four-fold increase in additional capacity when the distribution is weighted towards 50km compared to 10 km (Table 8).

Scenario 3	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	26.3 ± 20.8	8.7 ± 6.2
Middle Muir	0.097	476.9 ± 142.2	141.3 ± 36.5
Clyde	0.149	1179.8 ± 180.5	348.0 ± 53.1
Craig	0.075	310.2 ± 87.4	92.2 ± 28.4

Table 5 – Consumption of head room by an even distribution of 3.4 MW turbines. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Scenario 4	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	46.7 ± 36.0	14.7 ± 10.6
Middle Muir	0.097	872.5 ± 222.8	257.6 ± 65.5
Clyde	0.149	2147.6 ± 330.7	632.6 ± 97.3
Craig	0.075	558.0 ± 165.1	165.1 ± 52.5

Table 6 – Consumption of head room the distribution of 3.4 MW turbines that is weighted towards 50 km. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room

are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Scenario 5	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	11.9 ± 11.2	4.3 ± 3.5
Middle Muir	0.097	216.9 ± 58.4	64.8 ± 17.2
Clyde	0.149	547.6 ± 89.7	162.1 ± 26.4
Craig	0.075	144.3 ± 43.8	43.4 ± 14.0

Table 7 – Consumption of head room the distribution of 3.4 MW turbines that is weighted towards 10 km. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Middle Muir - summary	Head room nm	Additional Capacity MW	Number of turbines
Scenario 3 – Linear Distribution	0.097	476.9	141.3
Scenario 4 – Weighted to 50 km	0.097	872.5	257.6
Scenario 5 – Weighted to 10 km	0.097	216.9	64.8

Table 8 – Summary of how the distribution of turbines affects the additional number of turbines and capacity before the threshold is breached. These values are when the simulation uses measured data from Middle Muir is used for each additional turbine.