Xi Engineering Consultants

Eskdalemuir Wind Turbine Seismic Vibration

Phase 4: Field Audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions

Report presented to: Scottish Government and Eskdalemuir Working Group (EWG)

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Document Summary

Seismic sensors were used to measure the amplitude of ground-waves produced by wind turbines at seven wind farms in the Eskdalemuir consultation zone. The data was normalised to produce conservative spectra that represent single wind turbines measured at a distance of 1 km. These spectra were used to fit curves 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). The cumulative amplitude estimated by the current budget algorithm that includes an appropriate safety factor for the data sets available at the time was compared to the curves fitted here. The current algorithm estimates that the cumulative amplitude of all wind turbines operational and in planning up to and including and Faw Side T2 is 0.3216 nm. When the same calculation is carried out using the measured data from this campaign and then is extrapolated to represent the different wind turbine manufacturers, the cumulative amplitude is 0.2054 nm. The algorithm therefore over-estimates the measured data by 36.1%. The over-estimate is consistent with initial estimates calculated in Phase 2 (between 21% and 43%), thus the conclusions made in Phase 2 with respect to headroom, installable capacity and exclusion zone remain unchanged. Whilst the measured data fitted still maintains conservatism, further budget could be released if an approach to removing background noise from measured data were agreed, and before and after measurements were made.

Action	Name	Date	Version	Amendment
Originator	Dr B Marmo	6th Dec 2021	V1	Issue
Checked by	Dr M P Buckingham	13th Dec 2021	V2	review
Revised by	Dr B Marmo	13th Dec 2021	V3	Revised Discussion
Checked by	R Horton	13th Dec 2021	V4	Review
Revised by	Dr B Marmo	14th Dec 2021	V5	Following internal review
Checked by	Dr D Crooks	14th Dec 2021	V6	Review
Revised by	Dr B Marmo	14th Dec 2021	V7	Following internal review
Review	Dr M P Buckingham	15th Dec 2021	V8	Draft Release
Revised by	R Horton	4th Feb 2022	V9	Revisions based on external feedback of v8
Revised by	Dr B. Marmo	8th Feb 2022	V10	Revisions based on external feedback of v8
Review	Dr M P Buckingham	9th Feb 2022	V11	Director Review
Review	R Horton	10th Feb 2022	V12	Review

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1. Introduction

With good wind conditions and proximity to population centres, southern Scotland has excellent potential for onshore wind 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 seismic measuring 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 vibration budget of 0.336nm. Each turbine currently contributes to the budget 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 this significant wind resource available in the area.

By design, the 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 vibrations produced by wind turbines and does not compromise the seismic array. 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, allows 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 constraints and 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 farms 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 cumulative seismic 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 EKA budget. 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 0.161nm when using the current algorithm, thus we have captured 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 budget algorithm. When decisions on data handling are required, a conservative approach to ensure that the detection capabilities of the Eskdalemuir seismic array are protected.

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)
- Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements (SGV_203_Tech_Report_v12)

2. 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 ground vibration produced by wind turbines. Xi developed an algorithm which is currently used by the Ministry of Defence (MoD) to calculate the worst-case cumulative effect of all wind turbines on the 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 creates a displacement spectrum (frequency vs seismic amplitude) that represents the seismic output 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 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 vibration is constant, it is possible to scale the seismic 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 estimating seismic vibration at the planning stage of a wind farm's development.

The algorithm includes a Frequency Dependant Weighting Function (FDWF) which accounts for the variation in transmission of low and high frequencies, to determine what is detected at the array. This function would be used to design distant specific mitigation measures if required.

The algorithm variables were adjusted in order to best match or 'fit' the algorithm with the seismic data. The algorithm was fitted using seismic data from operational wind farms in southern Scotland which was collected 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 2020 these machines represent an older generation of wind turbine.

A key observation from the measurement of these three wind farms was that the seismic 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 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 Ministry of Defence Subject matter experts (Dr D Bowers) who subsequently presented to the CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization) and was ultimately accepted by the Scottish Government. Adopting the new algorithm opened up over 1GW of onshore wind power within the 50km Eskdalemuir zone compared to the MoD's earlier approach.

3. Summary of measurements

The seismic amplitude at seven wind farms were measured between 30/04/2021 and 24/11/2021. Table 1 lists the model and dimension 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 (≥1MW) have been measured.

Farm	OtherName	Manufacturer	Model	Number of Turbines	Hub Height	Rotor
Craig Hill	(Carlesgil and Extension)	Nordex	N80	4	70	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	82	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 noise. Multiple sensors were deployed to cover sensor failure and local site conditions. It is accepted practice that the sensor with lowest background noise be used to represent each site. Table 2 lists the sensor with the lowest background noise at each wind farm and data from these sensors are used in all subsequent calculations.

The seismic signal detected 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).

Amplitude and topology of the seismic 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
Minnygap	SL4
Solwaybank	SL3
Ewe Hill	SL3

Table 2 Sensor at each wind farm with the lowest background noise level. Data from these sensors are used to represent each wind farm in subsequent calculations

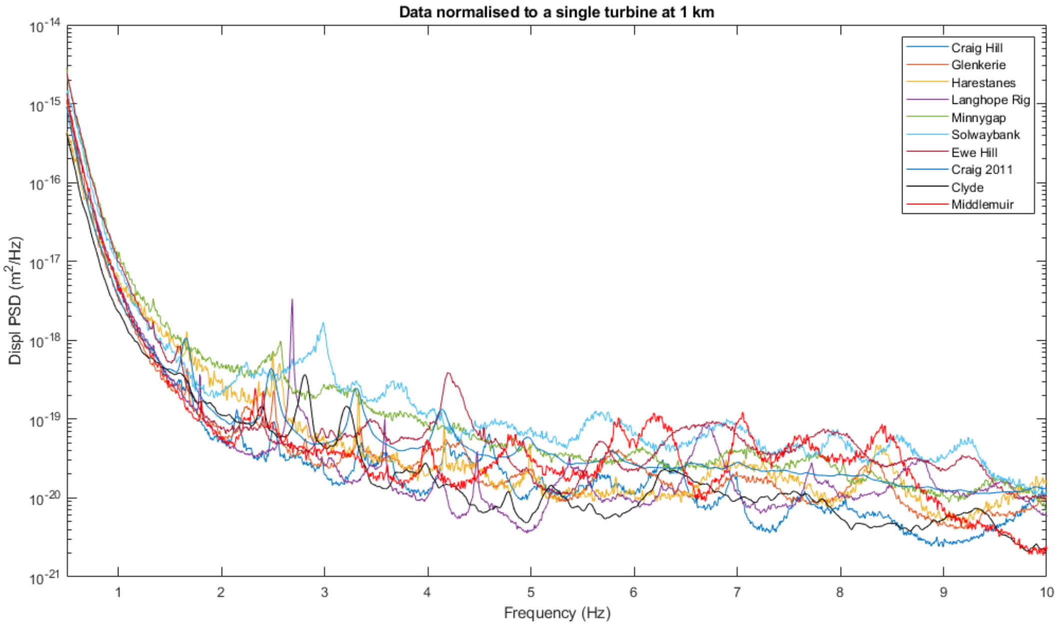


Figure 1 Seismic amplitude at each wind farm normalised to represent a single turbine measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

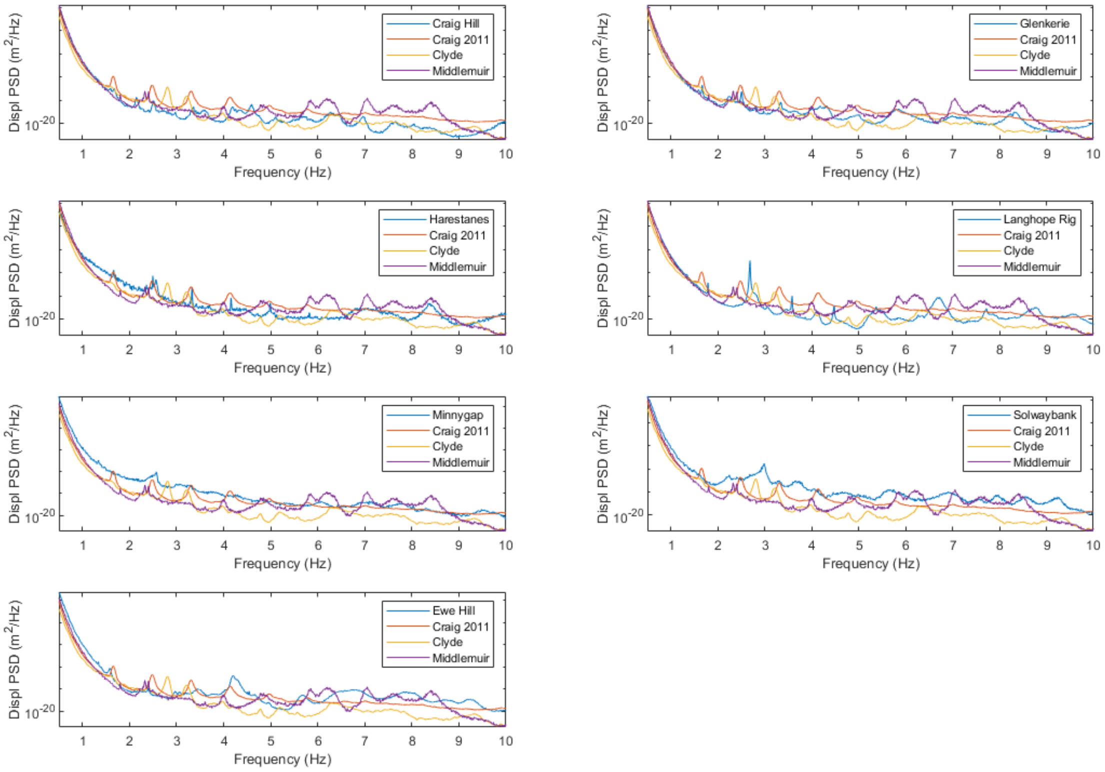


Figure 2 Seismic amplitude at each wind farm measured in the 2021 campaign compared to previously measured sites. The spectra have been normalised to represent a single turbine measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

3.1. Background noise at Solwaybank and Minnygap

The seismic signal recorded at each 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 ground vibration generated by wind turbines. This has been a common observation in previous wind turbine 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 the turbines' 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 outwith 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 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 the majority of seismic power measured at 12 m/s wind speed is attributed to sources outwith the wind turbines (Figure 4).

Given that the 12 m/s spectra from Minnygap and Solwaybank do not reflect the ground vibration produce 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.

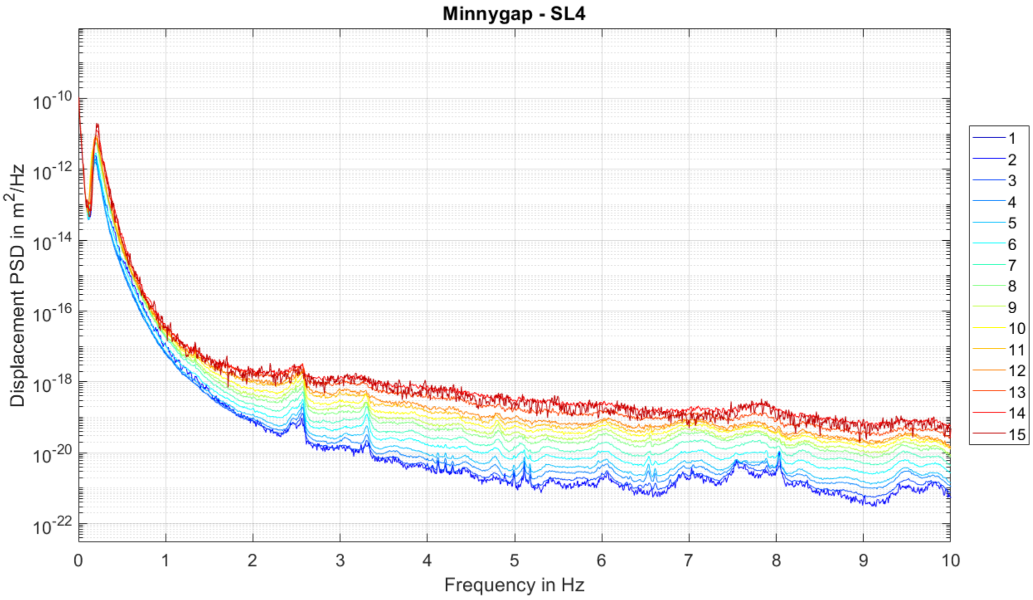


Figure 3 Variation of seismic amplitude with wind speed at Minnygap

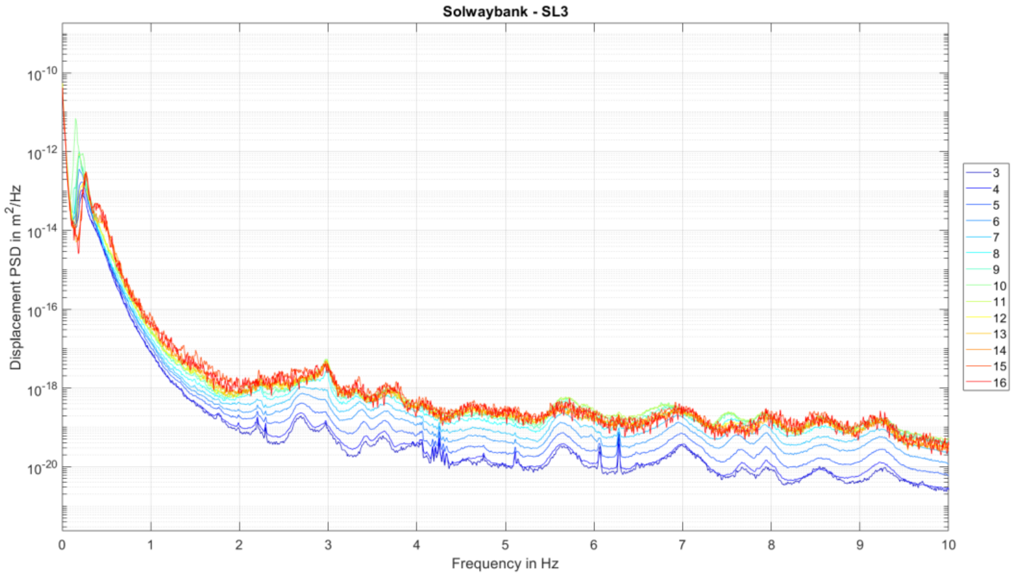


Figure 4 Variation of seismic amplitude with wind speed at Solwaybank

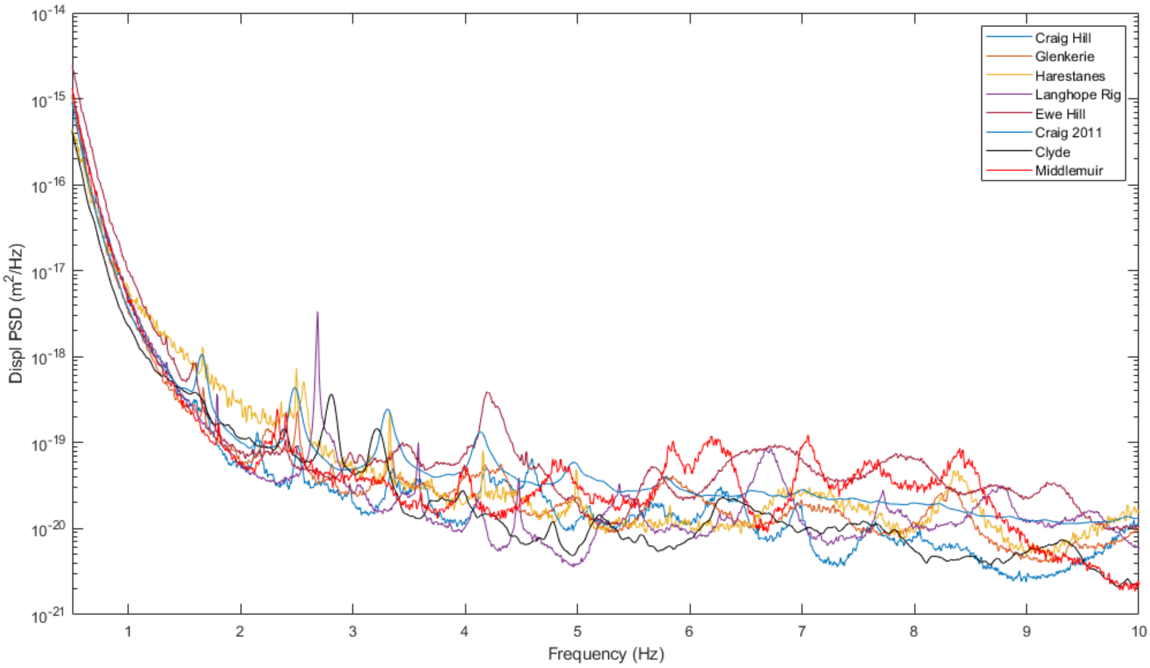


Figure 5 Seismic amplitude at each wind farm with Minnygap and Solwaybank excluded. The data are normalised to represent single turbines measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

3.2. 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 amplitudes calculated for the Gamesa wind turbines are unrealistically high.

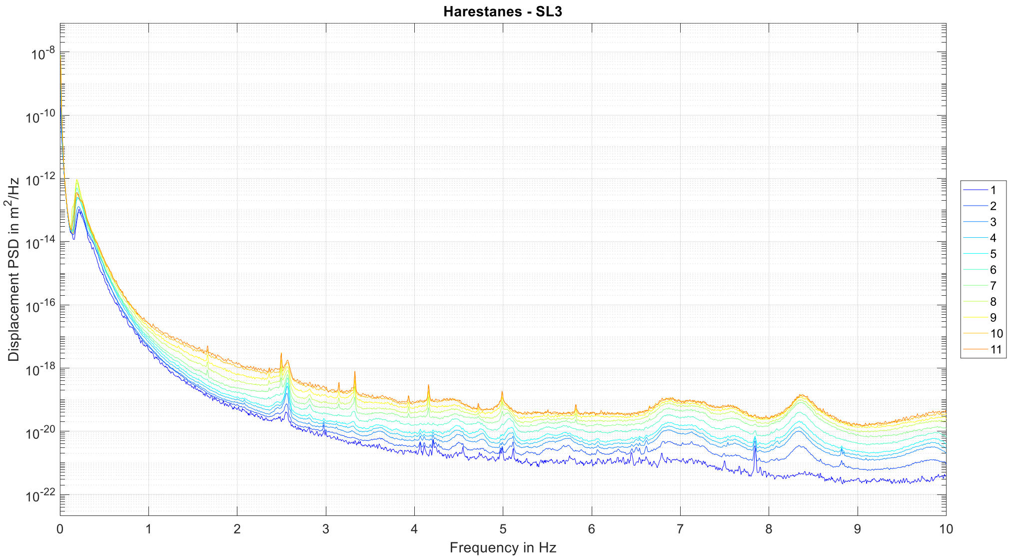


Figure 6 Variation of seismic amplitude with wind speed at Harestanes

4. Measured data compared to algorithm estimates

4.1. Results

The algorithm used to calculate the EKA budget uses a worst-case turbine to represent the spectra of any given wind turbine at a distance of 1 km (based on the turbines rotor diameter and hub height). This worst-case spectrum can be replaced by measured data at wind farms that have turbines with the same make and model as those measured here and previously. This approach considers that all seismic energy measured was 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. These amplitudes consider the distance from EKA using the Frequency-Distance Weighting Function (FDWF), which is consistent with the budget calculations. Table 3 also lists the impact as calculated by the budget using a worst-case turbine. 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 algorithm by between 23.1% and 42.7%. The cumulative measured impact for these wind turbines 31.1% lower than estimated by the budget.

Site	Farm	Number Of Turbines	Manufacturer	Model	Measured (nm)	Budget Algorithm (nm)	Over-estimate
2	Carlesgill (Craig)	5	Nordex	N80	0.0199	0.0314	36.7%
4	Langhope Rig	10	GE	GE1_6	0.0306	0.0403	24.1%
5	Clyde	152	Siemens	SWT2_3	0.0499	0.0740	32.5%
8	Minsca	16	Siemens	SWT2_3	0.0259	0.0336	23.1%
10	Ewe Hill	22	Siemens	SWT2_3	0.0602	0.0886	32.1%
12	Glenkerie	11	Vestas	V80	0.0115	0.0162	29.0%
19	Carlesgill (Craig) Ext	1	Enercon	E82	0.0100	0.0157	36.3%
58	Middle Muir	15	Senvion	M114	0.0036	0.0062	42.7%
Cumulative total					**0.0914**	**0.1326**	**31.1%**
6	Harestanes*	68	Gamesa	G8x	0.0662	0.0571	-15.88%

Table 3 Seismic impact of each wind farm based on measured data and considering the distance of each turbine from EKA using the FWDF curve. The estimate and the budget algorithm is also shown as is the ratio between the measured and algorithm-based values. *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.

5. Extrapolation to entire budget queue

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)” is used here as the basis of budget calculations. The spreadsheet was the most up to date available to Xi at the time of writing. One modification has been made to the spreadsheet in that the planning stage for Solwaybank was moved from “In Construction” to “Operational”. No sites have been removed or added to the table.

The spreadsheet contains wind turbine models that have not been measured and cannot therefore be represented with directly measured data. Instead, data from specific manufacturers (makes) have been extrapolated to different models based on their rotor diameter and hub height (e.g., Nordex N80 extrapolated to represent a Nordex N132). To extrapolate the data, the method 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 were 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 is followed here, where the coefficients are fitted to Craig for Nordex and Enercon turbines, Langhope Rig for GE, Harestanes for Gamesa and Glenkerie for Vestas. The fitted coefficients from previous reports for Clyde represents Siemens turbines and for Middle Muir represents Senvion.

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

$$\boldsymbol{WCT}_{(\boldsymbol{f},\boldsymbol{vw},\boldsymbol{A},\boldsymbol{f}_{\boldsymbol{BP}})} = \boldsymbol{OBN}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}})} + \boldsymbol{BM1}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A})} + \boldsymbol{BM2}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A})} + \boldsymbol{BM3}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A})} + \boldsymbol{BP}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A},\boldsymbol{f}_{\boldsymbol{BP}})}$$

where *WCT* is the synthetic spectra used to represent the turbine, *OBN* is the operational broadband noise, *BM1 BM2* and *BM3* are the three 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 impact of the fitted data was assessed following the method detailed in Section 4.1 and Table 4 shows that there is good agreement between measured and fitted spectra.

Wind Farm	Impact based on directly measured spectra (nm)	Impact based on fitted spectra (nm)
Carlesgill (Craig)	0.0199	0.0227
Langhope Rig	0.0306	0.0268
Clyde	0.0499	0.0444
Harestanes	0.0662	0.0525
Ewe Hill	0.0602	0.0721
Middle Hill - Glenkerie	0.0115	0.0113
Carlesgill (Craig) Ext	0.0100	0.0118
Middle Muir	0.0036	0.0049
Cumulative total	0.1099	0.1070

Table 4 Comparison of impact of each wind farm when calculated directly for the measured spectra (Table 3) and when calculated using the spectra fitted with coefficients listed in Appendix A.

5.1.1. 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 7). 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 and the mature wind farm having less activity related to installation and servicing than was the case when the then new 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 turbines makes. To fit for each make, the amplitude of the normalised spectrum was adjusted to account for the numbers 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 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, a conservative approach is followed here, and the double counted values used.

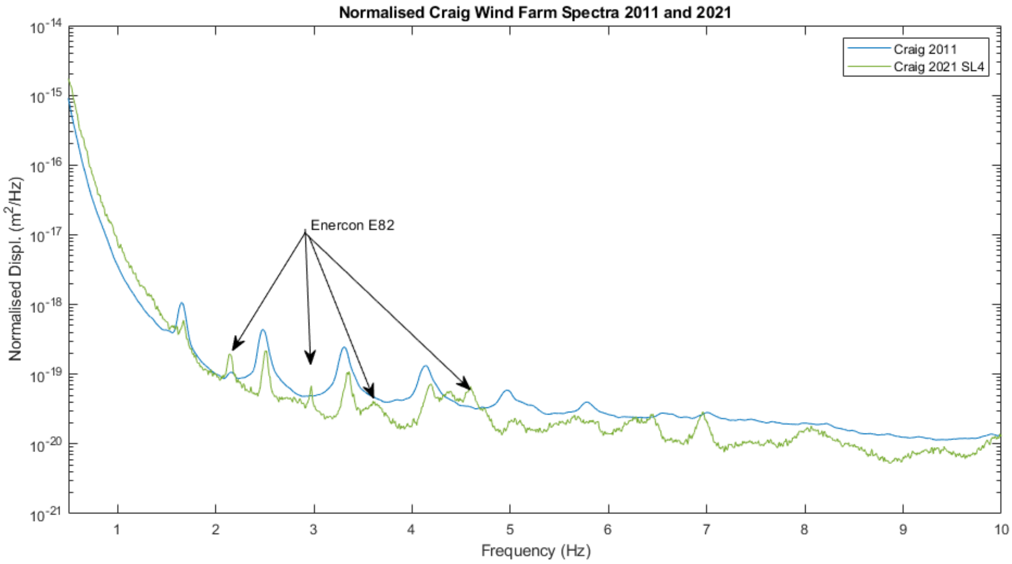


Figure 7 Comparison of data measured at Craig wind farm in 2011 when four Nordex N80 turbines were present compared to 2021 when the wind farm has an addition two Enercon E82 turbines.

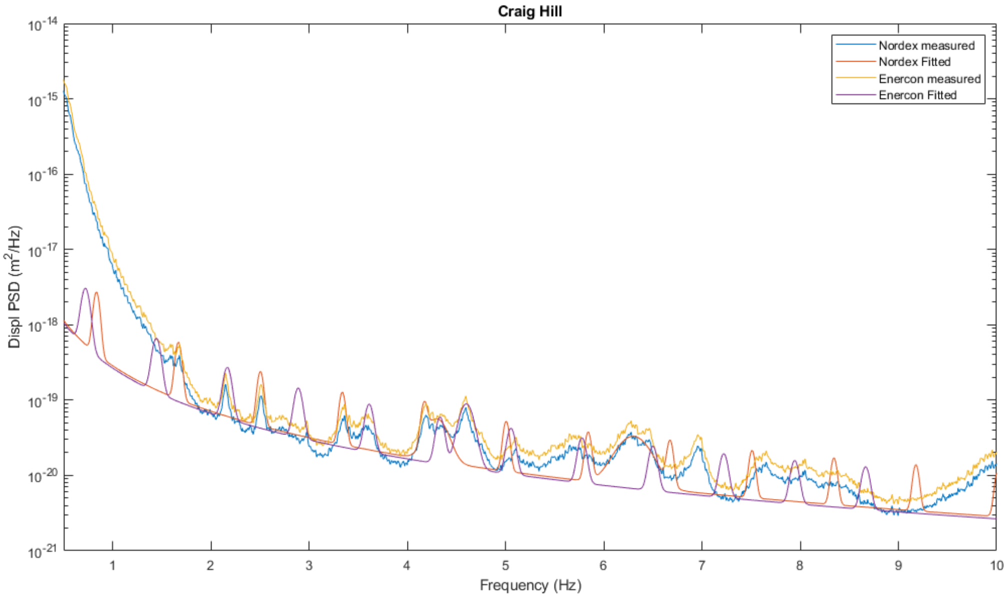


Figure 8 Fitting of coefficient to define the spectra used to extrapolate Nordex and Enercon turbines. The initial normalisation to a single turbine at 1 km was based on six turbines at Craig wind farm. The measured spectrum has been adjusted to account for there being two Enercon turbines and four Nordex, so that spectral peaks used for fitting have the correct amplitude.

5.1.2. 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 the 60 m hub height (see Appendix B).

5.1.3. Unknown and unmeasured turbines

Many wind farms in the budget queue are at the planning stage and have yet to determine which wind turbine will be installed at their proposed farm. Further, the single wind sub MW (500 kW) turbine listed as West of M6 Todhill was an operational EWT wind turbine for which there is no measured data. These wind farms required a fitted spectra to estimate their seismic contribution when extrapolating measured data to the entire queue.

The measurement of Langhope Rig had amplitudes closest to those estimated by the worst-case turbine in the budget algorithm (see Table 3) for turbines that are still in production and is a viable candidate for future sites in the consultation zone (Gamesa turbines at Harestanes are no longer in production). Following a conservative approach, the spectra representing GE wind turbines based on Langhope Rig has been used to estimate the contribution of all unknown turbines within the queue and the single sub MW class EWT.

5.1.4. Budget queue assumptions

The calculations provided below assume that the grid references, turbine dimensions and turbine manufacturers provided in the *20118 EKA Audited Tables Final V4- BASE.xlsx* are correct. To be consistent with the work detailed in Phase 2 (*SGV_202_Tech_Report_v07*) the budget is calculated for all turbines that are currently in the queue that do not breach the 0.336 nm threshold, i.e. all farms up to and including Cliffhope (submitted 29/09/2017) and the first two turbines (T1 and T2) from Faw Side (submitted 11/01/2018).

5.2. Results

The cumulative amplitude of all turbines in the budget queue was calculated up to and including Faw Side turbine T2. The current budget estimates that the cumulative impact of these turbines on EKA is 0.3216 nm. When measured seismic data is extrapolated using the approach detailed above, the cumulative impact is 0.2054 nm (Table 5). For clarity up to and including Cliffhope has been included in Table 4 as this is the final site which can be built out in full based on the current worst-case algorithm. The values based on the measurements presented here are 36.1% lower than the current budget estimate. Appendix C lists all wind farms in the queue as audited in Phase 3 (SGV_203_Tech_Report_v12) including those beyond Faw Side T2.

	Cumulative amplitude		Over-estimate
	Extrapolated from measurement (nm)	Standard EKA (nm)	
Queue to Cliffhope	0.1813	0.2762	34.4%
Queue to Faw Side T2	0.2054	0.3216	36.1%

Table 5 Comparison of cumulative impact on EKA based on measurement and the estimate provided by the current algorithmic approach. Values for the queue to Faw Side T2 is the point beyond which the 0.336 nm threshold is reached. Values up to Cliffhope (not including Faw Side turbines T1 and T2) are included for completeness.

6. Discussion

6.1. Uncertainties and assumptions

Measured data has been used here to better calculate the seismic contribution of wind turbines in the consultation zone. The seismic amplitude produced by a single wind turbine that is calculated by the budget algorithm was fitted to a relatively small dataset of just three wind farms that were 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 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 for the Eskdalemuir Working Group. Thus, the spectra for a GE turbine based on Langhope Rig, which was the highest of the turbines measured that are still in production, was used to represent farms with “unknown” turbine manufactures and the EWT turbine for which there is no measured data. 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.

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’s 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 were modelled using the operational broadband noise as measured and extrapolated from the Harestanes data.

6.2. Implications for head room and further capacity

Phase 2 of this work programme detailed in *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 – Summary of Results from Phase 2) used data from Craig, Clyde and Middle Muir to remove the safety factor from algorithm used to calculate the EKA budget and thereby assess potential head room. The conclusion of SGV_202_Tech_Report_v07 was that the algorithm over-estimated the impact by between 21% and 43%.

The work presented here follows a similar approach with a greatly increased data set. With the measurement provided here, combined with previous measurements, the dataset contains wind turbines that contribute 0.153 nm of the 0.161 nm currently installed and operating in the consultation zone. The method by which an over-estimate was assessed here is similar to that used in SGV_202_Tech_Report_v07. However, there is considerably less uncertainty in the over-estimate calculations given the very high proportion of turbines with which we now have seismic data. When measured data was extrapolated to the budget queue, an over-estimate of 36.1% was calculated (Table 5); this is in mid- to high-range concluded by SGV_202_Tech_Report_v07.

The Phase 2 work detailed in SGV_202_Tech_Report_v07 used a random population of the consultation zone to estimate how headroom in the budget provided by the removal of the safety factor in the budget algorithm with measured data might be converted to installable wind capacity. The report noted that conversion of budget headroom is very strongly dependent on the distribution of new wind turbines, where placing turbines preferentially further away from EKA resulted in higher installable capacity. Given a random distribution, SGV_202_Tech_Report_v07 estimated that the headroom would convert to between 480 MW and 1.2 GW. Given that the over-estimate calculated here falls in the mid- to high-range of that estimated in SGV_202_Tech_Report_v07, it follows that the installable capacity also lies between 480 MW and 1.2 GW (without additional measures to maximise deployment within the consultation zone, background removal or seismic mitigation). The installable capacity is highly dependent on the distribution of turbines and SGV_202_Tech_Report_v07 demonstrated skewing the random distribution toward 50km (away from 10 km would increase the conversion of headroom to installable capacity to between 860 MW and 2.1 GW. Again, given the similarity of results here it follows that the installable capacity based on the measurements here would be in the mid- to high-range for a similar distribution. These two analyses assume that two turbines at Faw Side consume budget and no further Faw Side turbines. Should the two Faw Side turbines not be built then the increase in headroom would result is significantly higher installable capacity than that noted above.

6.3. Implication of exclusion zone

The Phase 2 work detailed in SGV_202_Tech_Report_v07 modelled how the radius of the exclusion zone affects installable wind energy capacity. The report showed that increasing the radius of the exclusion zone from 10 km to 15 km could result in a three-fold increase in the conversion of headroom to installable capacity. Given that the results presented here are within the range of those used in SGV_202_Tech_Report_v07 it follows that the conclusions of the report with respect to the exclusion zone are unchanged.

6.4. 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 just wind turbines make, would provide an additional increase in the available budget and 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 increases 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 would 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 would effectively reduce the seismic levels of the turbines and further increase capacity in the region, while continuing to rigorously protect the EKA Seismic Array.

7. Conclusion

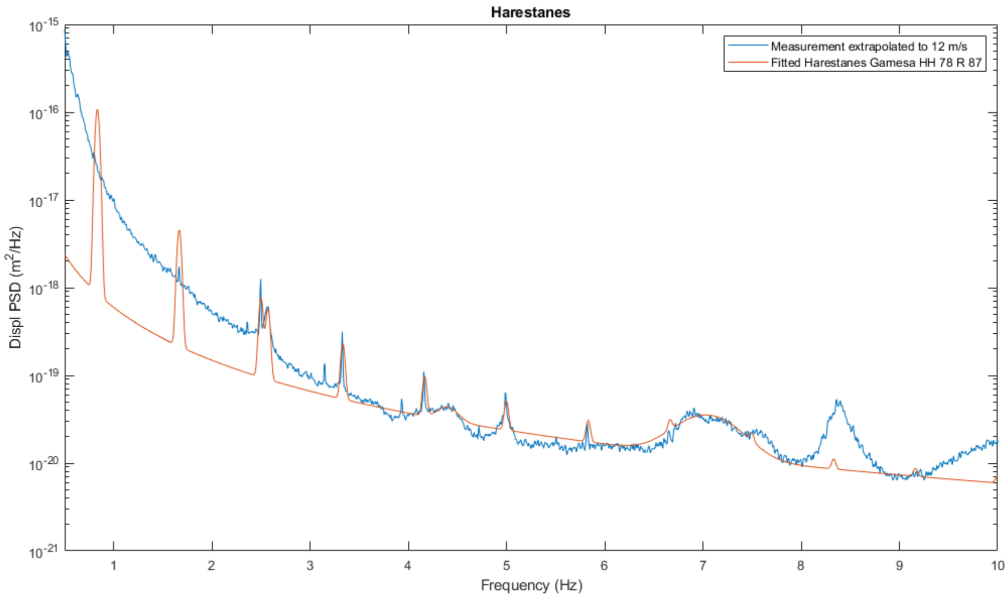
Data collected at seven wind farms combined with those from previous measurements allowed an assessment of the contribution of wind turbines to background seismic noise at Eskdalemuir Seismic Array. Currently, the seismic contribution is estimated using an algorithm based on the size of wind turbines and their distance to the EKA and includes a data set appropriate safety factor. The current algorithm estimates that the noise threshold of 0.336 nm will be breached by the third turbine at Faw Side (T3). The algorithm estimates that the contribution of all wind turbines in the budget queue up to and including Faw Side T2 is 0.3216 nm. Measured data was fitted to represent all the major turbine manufacturers in the consultation zone. Based on the extrapolation of data for each manufacturer (whilst maintaining conservatism) the contribution of all wind turbines in the budget queue up to and including Faw Side T2 is 0.2054nm. The algorithm therefore over-estimates the measured data by 36.1%. The over-estimate is consistent with initial estimates made with Phase 2 (between 21% and 43%), thus the conclusions made in Phase 2 with respect to headroom, installable capacity and exclusion zone are unchanged. Whilst the measured data fitted still maintains conservatism, further budget could be released if an approach to removing background noise from measured data were agreed, and before and after measurements were made.

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

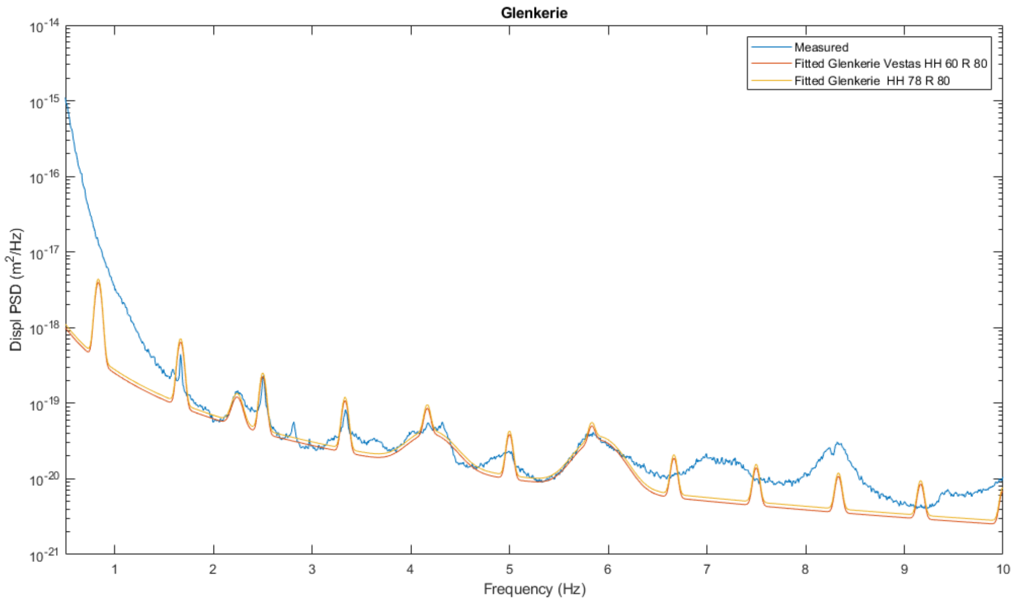
Coefficients	Standard EKA	Nordex	Siemens	Enercon	Vestas	Gamesa	GE	Senvion
Blade pass amplitude multiplier	2.8739E-25	1.87E-25	2.8739E-25	1.6e-25	2.87E-25	4.59E-24	2.69E-25	8E-25
Blade pass amplitude exponent	1.76	2.25	4	2.25	2.7	4.62	2.76	3.5
Blade pass shape parameter	0.04	0.03	0.04	0.04	0.03	0.02	0.02	0.03
Bending mode 1 amplitude multiplier	9.2303E-26	0	2.6152E-26	0	9.3E-27	4.85E-26	2.9E-25	8.1E-27
Frequency of bending mode 1	2.808	2.96	2.808	2.96	2.24	2.57	2.68	4.8
Bending mode 1 shape parameter	0.05	0.055	0.05	0.055	0.05	0.02	0.01	0.1
Bending mode 2 amplitude multiplier	0	5E-27	0	1e-26	3.3E-27	1.25E-27	1.8E-27	0
Frequency of bending mode 2	2.808	4.3	2.808	4.6	4.2	4.4	4.1	4.8
Bending mode 2 shape parameter	0.05	0.1	0.05	0.07	0.2	0.1	0.05	0.1
Bending mode 3 amplitude multiplier	0	3.15E-27	0	0	3.3E-27	2.30E-27	2.3E-27	0
Frequency of bending mode 3	2.808	6.3	2.808	5.7	5.9	7.04	5.4	4.8
Bending mode 3 shape parameter	0.05	0.16	0.05	0.23	0.2	0.3	0.14	0.1
Operational broadband noise multipliers	2.2282E-26	3.47e-26	2.2282E-26	3.47e-26	3.23E-26	5.85E-26	1.53E-26	3.5E-26
Tip Speed (m/s)	77.49	69.9	77.49	60.5	69.8	75.9	77.49	69.5

Coefficients used in the representations of seismic output of wind turbines manufacturers. 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 two additional bending modes. The Standard EKA coefficients are those currently used by the budget algorithm and include a factor of safety.

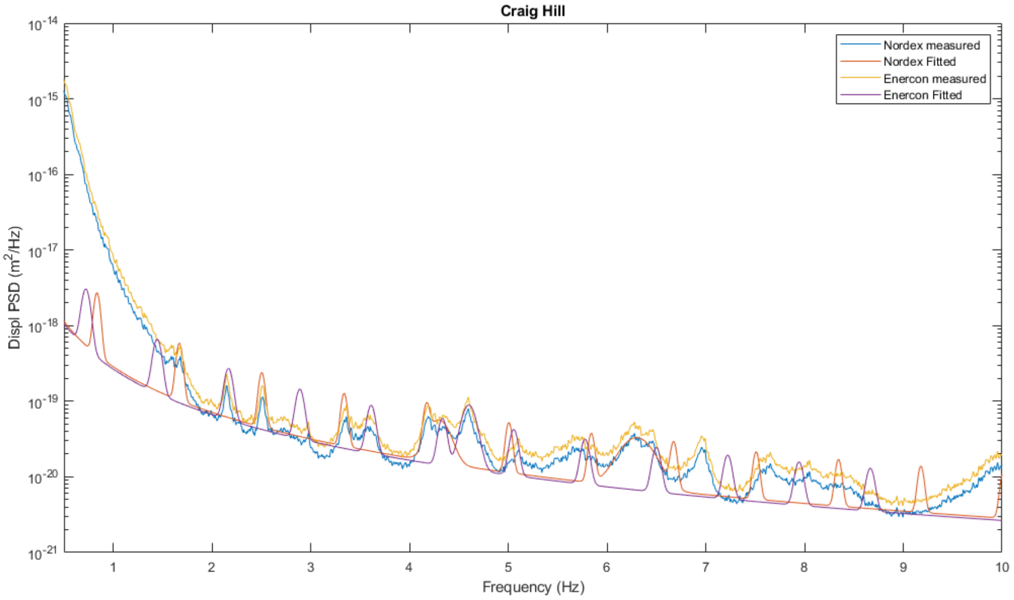
9. Appendix B – Fitting of coefficients to represent different manufacturers

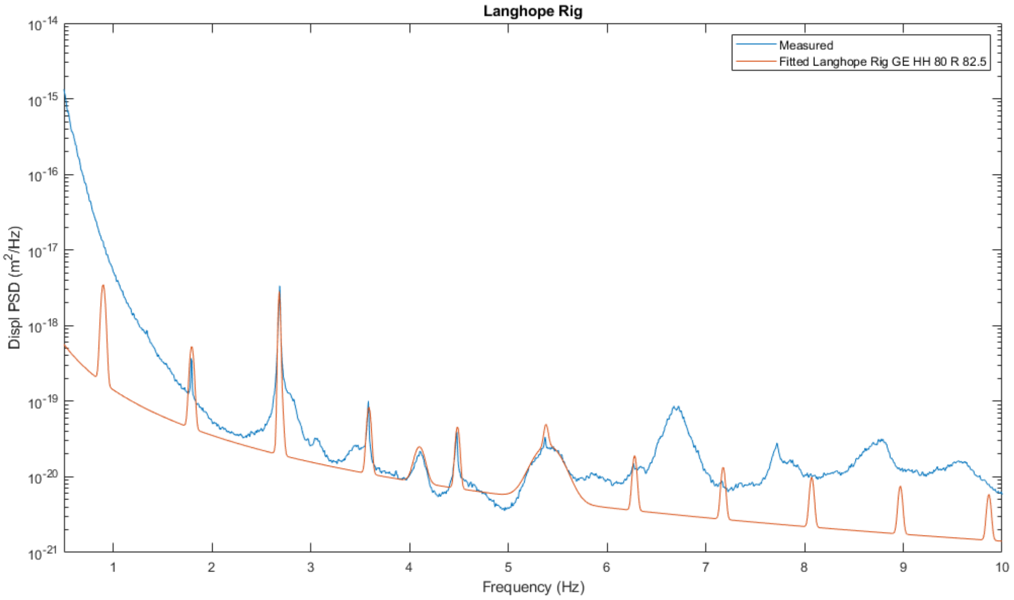


Harestanes



Glenkerie


Craig Hill
Nordex measured
Nordex Fitted
Enercon measured
Enercon Fitted
Displ PSD (m^2/Hz)
Frequency (Hz)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
1
2
3
4
5
6
7
8
9
10


Langhope Rig
Measured
Fitted Langhope Rig GE HH 80 R 82.5
Displ PSD (m^2/Hz)
Frequency (Hz)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
1
2
3
4
5
6
7
8
9
10

10. Appendix C Assessment of budget queue

* Shaded cells show cumulative amplitude that exceed the 0.336 nm threshold

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
1	Bowbeat	24	1.3	31.2	Nordex	Nordex	0.00320	0.00442	0.0032	0.0044
2	Carlesgill	5	2.5	12.5	Nordex	Enercon	0.02268	0.03137	0.0229	0.0317
3	Halkburn - Longpark	19	2	38	Senvion	Senvion	0.00431	0.00560	0.0233	0.0322
4	Langhope Rig	10	1.5	15	GE	GE	0.02684	0.04029	0.0355	0.0516
5	Clyde	152	2.3	349.6	Siemens	Siemens	0.04443	0.07399	0.0569	0.0902
6	Harestanes	68	2	136	Gamesa	Gamesa	0.05248	0.05714	0.0774	0.1068
7	Dalswinton	15	2	30	Senvion	Senvion	0.00754	0.01026	0.0778	0.1073
8	Minsca	16	2.3	36.8	Siemens	Siemens	0.02035	0.03364	0.0804	0.1124
9	Carcant	3	2.3	6.9	Siemens	Siemens	0.00055	0.00079	0.0804	0.1124
10	Ewe Hill	22	2.3	50.6	Siemens	Siemens	0.05203	0.08858	0.0958	0.1431
11	Andershaw	11	3.3	36.3	Vestas	Vestas	0.00364	0.00498	0.0958	0.1432
12	Middle Hill - Glenkerie	11	2	22	Vestas	Vestas	0.01132	0.01621	0.0965	0.1441
13	Langshaw Farm	1	0.05	0.05	unknown	GE	0.00015	0.00018	0.0965	0.1441
14	Aikrigg Cottage	1	0.006	0.006	unknown	GE	0.00002	0.00002	0.0965	0.1441
15	Kingstown Ind Estate	1	0.015	0.015	unknown	GE	0.00003	0.00003	0.0965	0.1441
16	Lammerlaw Farm 7153	1	0.011	0.011	unknown	GE	0.00009	0.00010	0.0965	0.1441
17	Brunstock Close	1	0.006	0.006	unknown	GE	0.00002	0.00002	0.0965	0.1441
18	Minnygap	10	2	20	Nordex	Nordex	0.02168	0.03168	0.0989	0.1476
19	Carlesgill Ext	1	2.5	2.5	Enercon	Enercon	0.01179	0.01572	0.0996	0.1484

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
20	Land East of Braidwood	1	0.006	0.006	unknown	GE	0.00009	0.00011	0.0996	0.1484
21	Westmill Farm	1	0.11	0.11	unknown	GE	0.00006	0.00007	0.0996	0.1484
22	Windyknowe	1	0.006	0.006	unknown	GE	0.00004	0.00004	0.0996	0.1484
23	Land NW of Ferniehaugh	2	0.06	0.12	unknown	GE	0.00006	0.00007	0.0996	0.1484
24	Lochmailing	1	0.015	0.015	unknown	GE	0.00010	0.00012	0.0996	0.1484
25	Threepwood	1	0.015	0.015	unknown	GE	0.00007	0.00008	0.0996	0.1484
26	Lauder B	2	0.12	0.24	unknown	GE	0.00009	0.00011	0.0996	0.1484
27	Rennieston Edge	1	0.06	0.06	unknown	GE	0.00004	0.00005	0.0996	0.1484
28	Meadowside Cottage	1	0.02	0.02	unknown	GE	0.00009	0.00011	0.0996	0.1484
29	Mosshouses Farm	1	0.015	0.015	unknown	GE	0.00006	0.00008	0.0996	0.1484
30	Land SW of Larkhill	1	0.015	0.015	unknown	GE	0.00006	0.00008	0.0996	0.1484
31	Hall Burn	6	2.2	13.2	Vestas	Vestas	0.00393	0.00554	0.0997	0.1485
32	Muirlea Farm	2	0.04	0.08	unknown	GE	0.00014	0.00017	0.0997	0.1485
33	Whinney Rig	1	0.1	0.1	unknown	GE	0.00033	0.00041	0.0997	0.1485
34	Hillfield	1	0.005	0.005	unknown	GE	0.00002	0.00003	0.0997	0.1485
35	Cargo Farm Cottage	2	0.04	0.08	unknown	GE	0.00010	0.00012	0.0997	0.1485
36	Land NW of The Batts	1	0.0015	0.0015	unknown	GE	0.00005	0.00006	0.0997	0.1485
37	Burnhouse	1	0.0015	0.0015	unknown	GE	0.00006	0.00007	0.0997	0.1485
38	The Beeches	1	0.02	0.02	unknown	GE	0.00008	0.00009	0.0997	0.1485
39	Symington Mains Farm	1	0.02	0.02	unknown	GE	0.00007	0.00009	0.0997	0.1485
40	Midhill	1	0.015	0.015	unknown	GE	0.00009	0.00011	0.0997	0.1485
41	Newton of Wiston	1	0.015	0.015	unknown	GE	0.00006	0.00008	0.0997	0.1485
42	Newtonhead	1	0.06	0.06	unknown	GE	0.00011	0.00014	0.0997	0.1485

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
43	Gaups Mill	1	0.01	0.01	unknown	GE	0.00003	0.00004	0.0997	0.1485
44	South Melbourne Farm	1	0.006	0.006	unknown	GE	0.00004	0.00005	0.0997	0.1485
45	Walston Braehead Farm	3	0.06	0.18	unknown	GE	0.00014	0.00017	0.0997	0.1485
46	Easton Farm	1	0.02	0.02	unknown	GE	0.00007	0.00008	0.0997	0.1485
47	Pumro Fell	1	0.0015	0.0015	unknown	GE	0.00005	0.00006	0.0997	0.1485
48	Rivox	1	0.015	0.015	unknown	GE	0.00044	0.00055	0.0997	0.1485
49	Braco Farm	2	0.03	0.06	unknown	GE	0.00007	0.00008	0.0997	0.1485
50	Land at Arthurshiels	1	0.02	0.02	unknown	GE	0.00009	0.00010	0.0997	0.1485
51	Hyndshawland	1	0.02	0.02	unknown	GE	0.00009	0.00011	0.0997	0.1485
52	Clyde Extension	54	3	162	Siemens	Siemens	0.02853	0.04801	0.1037	0.1561
53	Glentaggart	5	3	15	unknown	GE	0.00176	0.00257	0.1037	0.1561
54	Kirkpatrick Hill	1	0.11	0.11	unknown	GE	0.00014	0.00017	0.1037	0.1561
55	East Millrig	1	0.015	0.015	unknown	GE	0.00011	0.00014	0.1037	0.1561
56	Solwaybank	15	2	30	Vestas	Vestas	0.02592	0.03748	0.1069	0.1605
57	Mallshill	1	0.005	0.005	unknown	GE	0.00006	0.00007	0.1069	0.1605
58	Middle Muir	15	3.4	51	Senvion	Senvion	0.00491	0.00623	0.1070	0.1606
59	Brockhouse	1	0.011	0.011	unknown	GE	0.00006	0.00007	0.1070	0.1606
60	Broomhills	1	0.01	0.01	unknown	GE	0.00006	0.00008	0.1070	0.1606
61	Land SW of Copland Farm	1	0.011	0.011	unknown	GE	0.00011	0.00013	0.1070	0.1606
62	Land N of Midtown Farm	1	0.05	0.05	unknown	GE	0.00010	0.00012	0.1070	0.1606
63	Birkenside Farmhouse	1	0.05	0.05	unknown	GE	0.00010	0.00012	0.1070	0.1606

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
64	Libberton Mains Farm	1	0.02	0.02	unknown	GE	0.00007	0.00008	0.1070	0.1606
65	Cloich Forest	12	4.8	57.6	Nordex	Nordex	0.00598	0.00868	0.1072	0.1609
66	Bankhouse	1	0.012	0.012	unknown	GE	0.00004	0.00005	0.1072	0.1609
67	Lammerlaw	2	0.022	0.044	unknown	GE	0.00012	0.00014	0.1072	0.1609
68	Cormiston Farm	1	0.02	0.02	unknown	GE	0.00012	0.00014	0.1072	0.1609
69	Hartsop	1	0.015	0.015	unknown	GE	0.00010	0.00012	0.1072	0.1609
70	Parkhouse Farm	2	0.02	0.04	unknown	GE	0.00010	0.00013	0.1072	0.1609
71	Shankfield Head	2	0.02	0.04	unknown	GE	0.00010	0.00012	0.1072	0.1609
72	Cambwell	1	0.011	0.011	unknown	GE	0.00013	0.00016	0.1072	0.1609
73	South of Hyndfordwells	3	0.18	0.54	unknown	GE	0.00014	0.00017	0.1072	0.1609
74	Rose Cottage	1	0.006	0.006	unknown	GE	0.00003	0.00004	0.1072	0.1609
75	Hillend Farm	1	0.011	0.011	unknown	GE	0.00013	0.00016	0.1072	0.1609
76	Glenkerie Extension	6	2.5	15	Senvion	Senvion	0.00820	0.01142	0.1075	0.1613
77	Deanfoot Farmhouse	1	0.05	0.05	unknown	GE	0.00009	0.00011	0.1075	0.1613
78	Lion Hill	4	2.3	9.2	Vestas	Vestas	0.01007	0.01472	0.1080	0.1620
79	West of Hyndfordwells Farm	1	0.02	0.02	unknown	GE	0.00006	0.00007	0.1080	0.1620
80	Crookedstane Farm	4	2.3	9.2	Vestas	Vestas	0.00811	0.01182	0.1083	0.1624
81	Windy Edge	9	22.5	202.5	Nordex	Nordex	0.02491	0.03572	0.1111	0.1663
82	Blackdyke	1	0.01	0.01	unknown	GE	0.00005	0.00006	0.1111	0.1663
83	Cottage Farmhouse	1	0.011	0.011	unknown	GE	0.00006	0.00007	0.1111	0.1663
84	Lampits Farm 2	1	0.25	0.25	unknown	GE	0.00016	0.00021	0.1111	0.1663
85	Land NW of West Morriston Farm	1	0.05	0.05	unknown	GE	0.00012	0.00015	0.1111	0.1663

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
86	Solway re-sub (Beckburn)	9	3.45	31.05	Vestas	Vestas	0.00565	0.00803	0.1112	0.1665
87	Land East of Mossbank	2	0.011	0.022	unknown	GE	0.00014	0.00017	0.1112	0.1665
88	Twentyshilling Hill	9	4.2	37.8	Vestas	Vestas	0.00191	0.00253	0.1112	0.1665
89	Townfoot	1	0.01	0.01	unknown	GE	0.00009	0.00011	0.1112	0.1665
90	South Slipperfield Farmhouse	1	0.011	0.011	unknown	GE	0.00009	0.00012	0.1112	0.1665
91	Rose Cottage (9812)	1	0.25	0.25	unknown	GE	0.00003	0.00004	0.1112	0.1665
92	Whitelaw Brae	14	4.2	58.8	unknown	GE	0.03175	0.04898	0.1157	0.1735
93	East of Newton of Covington	2	0.02	0.04	unknown	GE	0.00010	0.00012	0.1157	0.1735
94	Bailey Town Farm	1	0.01	0.01	unknown	GE	0.00015	0.00019	0.1157	0.1735
95	Kilravoch	1	0.0012	0.0012	unknown	GE	0.00002	0.00002	0.1157	0.1735
96	South Melbourne Farm 2	1	0.011	0.011	unknown	GE	0.00010	0.00012	0.1157	0.1735
97	SW of Kettleshill Farmhouse	1	0.012	0.012	unknown	GE	0.00003	0.00004	0.1157	0.1735
98	West of M6 Todhills	1	0.5	0.5	EWT	GE	0.00047	0.00063	0.1157	0.1735
99	Trough Head Farm	2	0.01	0.02	unknown	GE	0.00025	0.00030	0.1157	0.1735
100	72 Carlisle Road	2	0.085	0.17	unknown	GE	0.00025	0.00032	0.1157	0.1735
101	Clackmae Farm	1	0.1	0.1	unknown	GE	0.00016	0.00020	0.1157	0.1735
102	East of Whitslaid Farm	2	0.05	0.1	unknown	GE	0.00008	0.00010	0.1157	0.1735
103	Crossdykes	10	4.8	48	Nordex	Nordex	0.09860	0.14087	0.1520	0.2235
104	Whins Farm	1	0.085	0.085	unknown	GE	0.00050	0.00067	0.1520	0.2235
105	Loganhead	8	3.2	25.6	GE	GE	0.05001	0.08009	0.1600	0.2374

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
106	Jockstown Farm	1	0.1	0.1	unknown	GE	0.00046	0.00061	0.1600	0.2374
107	Burnswark Garage	1	0.5	0.5	unknown	GE	0.00063	0.00085	0.1600	0.2374
108	Wauchope & Newcastleton Forests	90	3.4	306	unknown	GE	0.02808	0.04199	0.1625	0.2411
109	North Lowther	30	5	150	unknown	GE	0.00889	0.01347	0.1627	0.2415
110	Hopsrig	12	3.5	42	Siemens	Siemens	0.06471	0.11242	0.1751	0.2664
111	Pines Burn	12	3.3	39.6	Nordex	Nordex	0.02100	0.03108	0.1764	0.2682
112	Priestgill	7	3.2	22.4	GE	GE	0.00672	0.01015	0.1765	0.2684
113	Land SE of Scotston Bank Farm	3	0.015	0.045	unknown	GE	0.00014	0.00017	0.1765	0.2684
114	Cliffhope	46	7	322	unknown	GE	0.04134	0.06528	0.1813	0.2762
115	Faw Side	45	7	315	unknown	GE	0.38546	0.65535	0.4260	0.7112
116	Little Heart Fell	9	5.7	51.3	Nordex	Nordex	0.10750	0.15547	0.4393	0.7280
117	Twentyshilling hill revised	9	4.2	37.8	Vestas	Vestas	0.00293	0.00397	0.4393	0.7280
118	Daer	15	5.8	87	unknown	GE	0.03632	0.05827	0.4408	0.7303
119	Scoop Hill	78	7	546	unknown	GE	0.50247	0.85396	0.6684	1.1237
120	Callisterhall	13	6	78	Vestas	Vestas	0.07393	0.10932	0.6725	1.1290
121	Priestgill resub	7	5.6	39.2	Vestas	Vestas	0.00982	0.01434	0.6726	1.1291
122	Westerkirk	20	4	80	unknown	GE	0.28381	0.47791	0.7300	1.2260
123	Loganhead resub	8	4.8	38.4	Nordex	Nordex	0.06845	0.09898	0.7332	1.2300
124	Hopsrig resub	12	4.15	49.8	Vestas	Vestas	0.13510	0.19494	0.7456	1.2454
125	Harestanes South	8	5.5	44	unknown	GE	0.02590	0.04141	0.7460	1.2461
126	Greystone Knowe	15	4.5	67.5	unknown	GE	0.00555	0.00853	0.7460	1.2461
127	Whitelaw resub	12	4.2	50.4	unknown	GE	0.03787	0.05914	0.7470	1.2475
128	Scawd Law	12	4.2	50.4	unknown	GE	0.00845	0.01272	0.7470	1.2476

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
129	Grayside	25	6.6	165	unknown	GE	0.02919	0.04621	0.7476	1.2484

11. 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

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

12. 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 6. The additional capacity and number of turbines listed in Table 6 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 7 lists how the head room converts to additional capacity when more turbines are built close to 50 km, while Table 8 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 9).

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 6 – 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 7 – 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 8 – 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 9 – 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.