Xi Engineering Consultants

Eskdalemuir Wind Turbine Seismic Vibration

Calculations to confirm maximum turbine seismic level to deploy minimum of 1GW deployment

Report presented to: Scottish Government

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Document Summary

Xi Engineering were engaged by the Scottish Government to provide this technical analysis to inform their On-shore wind Policy.

The list of wind turbines in Eskdalemuir Consultation Zone queue was audited and revised, and the cumulative seismic impact on the Eskdalemuir Seismic Array was re-calculated based on wind turbines measured in Phase 4. Using these revisions, it was calculated that all wind farms with MoD allocated budget, up to and including Scotston Bank wind farm have a cumulative impact of 0.21810 nm resulting in 0.25560 nm of head-room in the budget.

A Seismic Impact Limit (SIL) was studied as a potential method by which to optimise the additional capacity available within the consultation zone. It was determined that a Seismic Impact Limit of 0.00809 $nm.MW^{-0.5}$ will provide at least 1 GW of additional wind capacity in the consultation zone.

A randomised simulation of wind turbine placement and power was conducted to determine the probability distribution of installable power in the consultation zone. If the 0.25560 nm were consumed by a random distribution of wind turbines with the proviso that they do not exceed the Seismic Impact Limit of 0.00809 $nm.MW^{-0.5}$, then there is a reasonable expectation that at least 2.7 GW could be installed, with the median of the probability of an additional 4.3 GW of deployment within the region.

Action	Name	Date	Version	Amendment
Originator	Dr B. Marmo	29/6/2022	v1	Issue
Director review	Dr M P Buckingham	7/7/2022	v2	Review
Review	Dr Brett Marmo	11/7/2022	v3	Update tables
Review	Dr M P Buckingham	12/7/2022	v4	Review
Review	R. Horton	13/07/2022	v5	Review
Director review	Dr M P Buckingham	14/07/2022	v6	Review
Review	R Horton	14/07/2022	v7	Review
Director review	Dr M P Buckingham	14/07/2022	v8	Issue
Review	R Horton	14/07/2022	v9	Formatting
Modified	Dr B Marmo	27/10/2022	V10	Comments for D. Bowers
Director Review	Dr M P Buckingham	28/10/2022	V11	Review
Updated	R. Horton	13/01/2023	V12	Minor Corrections
Review	Dr B Marmo	13/01/2022	V13	Review for Release

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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. It is currently estimated that each turbine contributes to the budget based upon a worst-case hypothetical turbine. When using this hypothetical turbine, the vibration budget of 0.336nm has been reached. Using this approach, 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. Xi Engineering Consultants (Xi) conducted a large-scale survey of wind turbines in the Eskdalemuir consultation area (see *Phase 4: Field Audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions* Ref: SGV_204_Tech_Report_v12 issued 10/2/2022) to determine the as-built seismic impact of wind turbines in the EKA, whether there is head-room within the seismic budget for additional wind energy capacity, and if so, how much head-room is there.

The work detailed in SGV_204_Tech_Report_v12 demonstrated that there is significant head-room for additional wind turbines. Given the pressing nature of the Climate Crisis there is a strong motivation to optimise the additional capacity in the consultation zone such that the largest amount of wind energy can be installed whilst ensuring the EKA is not adversely affected.

Care must be taken to ensure the budget maximises the potential for onshore deployment while continuing to ensure the protection of the Eskdalemuir Seismic Array (EKA). Turbines sited close to the array require a disproportionate level of seismic budget, theoretically allowing a single windfarm to consume all the available budget released by prior work up to and including phase 4.

As described in the Phase 4 work, to minimise the impact of all developments on the EKA once approved, empirical evidence of the true Seismic Impact of the site could be collected and reported both before and after installation.

This suite of work (SGV-200 phases 1-4) deepened the understanding of the Seismic Impact of Wind Farms on the EKA based on larger data sets and newer Wind Turbine Technologies and has also discussed various ways that wind turbine deployment within the consultation zone could be optimised. There are several different and overlapping approaches that could assist in the maximisation of the onshore capacity of the EKA including but not limited to: extension of the exclusion zone, before and after measurements of all future developments and the introduction of a Seismic Impact Limit. This report (phase 5) presents the findings of calculations of the latter, potential Seismic Impact Limits

A potential approach for optimising the wind energy capacity of the consultation zone would be to set a limit on the impact that any one turbine has on EKA, i.e., set a nm/MW limit (where nm is the amplitude that arrives at EKA and MW is the capacity of the turbine). Such nm/MW limit would promote the placement of turbines further from EKA and the installation of turbines with low seismic output where turbines are in closer proximity to the array.

2. Background

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

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

Concerns were raised that vibrations from wind turbines might affect the ability of EKA to operate properly, and MoD were advised to set a maximum permissible background vibration budget within a 50km radius of the Eskdalemuir array in order to safeguard its effectiveness in accordance with the CTBT. Beyond 50km it was determined that the vibration contribution from a wind turbine is negligible and is not included in the vibration budget. The maximum vibration budget that was deemed to be acceptable from all wind turbines that might be built within 50km of the array was set at threshold amplitude of 0.336nm in the 4 to 5 Hz frequency range. This budget was subsequently agreed by the Comprehensive Test Ban Treaty Organisation (CTBTO) in Vienna.

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

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 now used by the MoD to allocate budget is effectively two turbines combined to provide a significant safety factor. The budget algorithm is designed with safety factors such that it over-predicts the output of any single turbine.

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

3. Revised EKA queue and Headroom

3.1. Revisions to the queue

In order to accurately calculate the numerical budget position, the budget queue was assessed by the Scottish Government to cleanse and update it up to the 26th June 2022. The following actions were taken during this process:

- Full audit of all sites and planning status
- All sites that have been withdrawn or refused with no option for appeal were removed.
- Constructed sites 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.
- Sites not built with no conditions and unknown turbine manufacturer have been allocated the GE results from Phase 4 to remain conservative (Please note, no evidence has been found in the public domain of confirmed MoD allocations after the Scotson Bank Development)
- All the sites within the Eskdalemuir region which have entered the planning system have now been included

The revised list of turbines within the consultation zone can be seen in section 9 – Appendix B

3.2. Budget Headroom Calculation

The seismic impact of each wind farm in the queue was assessed following the methodology detailed in the Phase 4 Report (SGV_204_Tech_Report_v12), whereby wind turbine spectra for given manufacturers were tightly fitted to measured data and extrapolated to different models based on their rotor diameter and hub height (e.g., measured Nordex N80 spectra extrapolated to represent a Nordex N132).

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. 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 SGV_204_Tech_Report_v12) for turbines that are available on the market. 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.

Many sites received confirmation from the MoD during the planning process of the MOD calculated budget for the site. Sites with planning permission and existing conditions or legal agreements with MoD have been allocated the calculated standard EKA budget.

Therefore, the Standard EKA algorithm (worst-case spectra) was used to assess the impact of these wind farms.

All sites which did not receive an objection from the MoD on seismic level 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 queue up to and including Scotston Bank is 0.21810 nm. This is significantly below the budget threshold of 0.336 nm. Given that the impact of farms adds in quadrature the head-room is 0.25560 nm:

$$\sqrt{0.336^2 - 0.21810^2} = 0.25560$$

4. Seismic impact limit to guarantee 1 GW

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

4.1. Impact dependence on turbine power

The seismic power produced by wind turbines has a close to linear relationship with their output power. Given this near linear relationship and that the amplitude from turbines add in quadrature, the impact of larger turbines is much greater than that of smaller turbines. Consider two 10 MW wind farms at the same distance from EKA: Farm A consists of ten 1 MW turbines, while Farm B has a single 10 MW turbine. The amplitude of each turbine at Farm A is 1 nm, while the amplitude of the single turbine at Farm B is 1 x 10 = 10 nm. The cumulative amplitude from Farms A & B:

$$A_{Total} = \sqrt{1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2 + 1^2} \qquad B_{Total} = \sqrt{10^2}$$

$$A_{Total} = \sqrt{10} \qquad B_{Total} = \sqrt{100}$$

$$A_{Total} = 3.16 \text{ nm} \qquad B_{Total} = 10 \text{nm}$$

While both Farm A and Farm B produce 10 MW, Farm A's impact of 3.16 nm is significantly less that Farm B's 10 nm. To account for this variation in impact with power output the seismic impact limit will be assessed as amplitude of impact per the square root of power with the units of $nm.MW^{-0.5}$:

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

This equation can be rearranged to calculate the maximum allowable impact amplitude for any given wind turbine based on its Maximum rated power:

$$Ampitude\ at\ EKA = Seismic\ Impact\ Limit\ \times \sqrt{Wind\ Turbine\ Rated\ Power}$$

where *Amplitude at EKA* is equivalent to impact.

4.2. Generalisation of rotor diameter and hub height

Future wind turbines that may be installed within the consultation zone will have a range of power outputs that will depend on their rotor's swept area and height. To calculate a Seismic Impact Limit independent of specific manufactures, the wind turbine specifications used by the EKA algorithm (hub height and rotor diameter) have been generalised. The power of turbines tends to be linearly dependent on the sweep area of the rotor, ergo, power goes with the square of rotor diameter. The hub heights of wind turbines are designed such that there is sufficient clearance of the blades with obstacles on or close to the ground so that hub height tends to go linearly with blade length, and therefore linearly with rotor diameter. To generalise the turbine design parameters for the consultation zone, the power, rotor and hub heights listed in the EKA budget queue were used to fit the square of rotor diameter to power output (Figure 1), and hub height to rotor diameter (Figure 2). The turbine design specifications were thereby generalised as:

$$Rotor\ Diameter = \frac{\sqrt{Power}}{0.0002771}$$

$$Hub\ Height = 0.8323 \times Rotor\ Diameter + 2.883$$

where the rotor diameter and hub height are in meters and the power is in megawatts. The numbers in the above equations represent those used to best fit the data shown in Figure 1 and Figure 2.

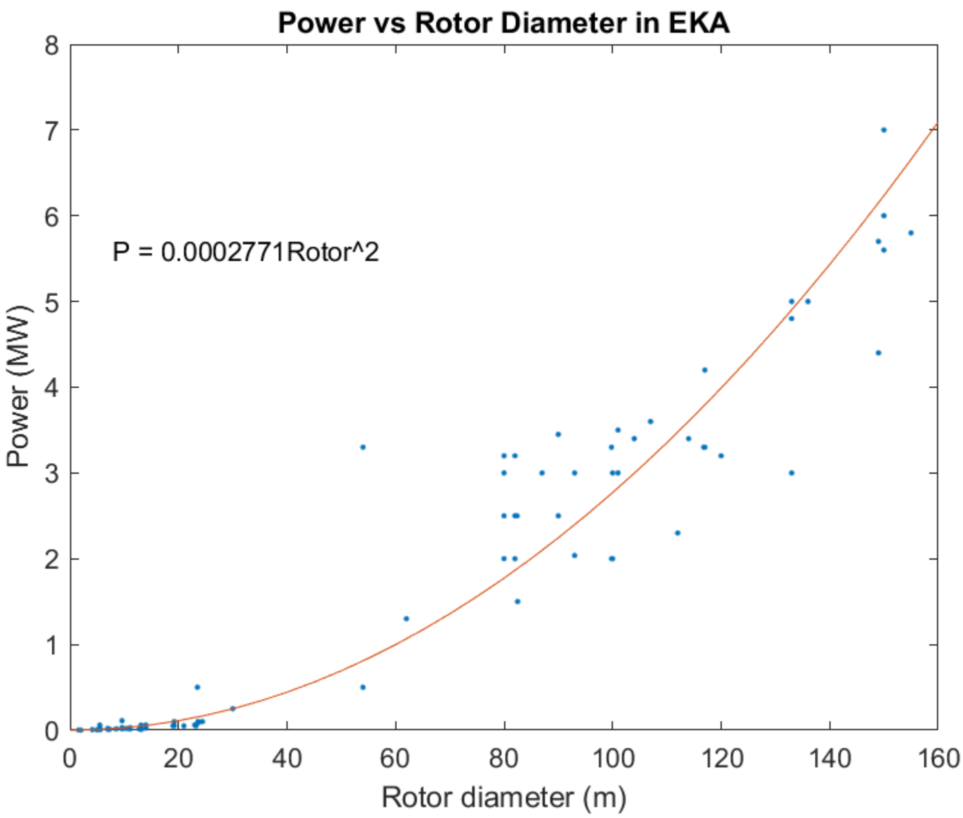


Figure 1 Relationship between rotor diameter and power for all turbines listed in the EKA budget queue

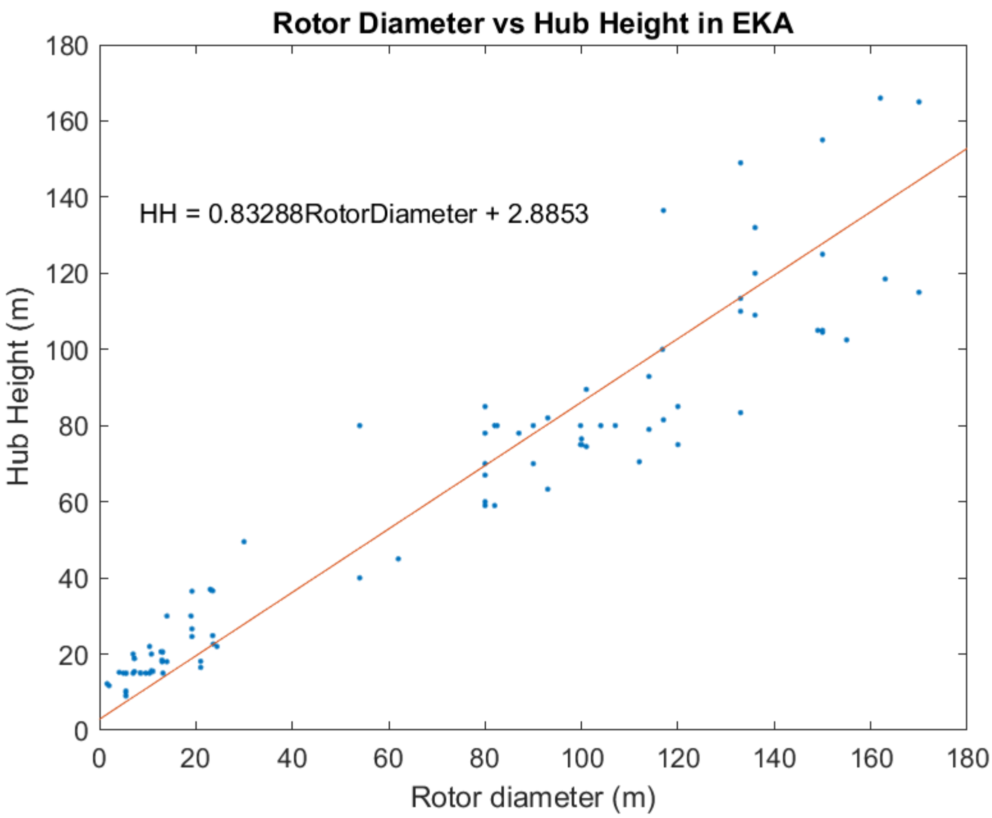


Figure 2 Relationship between hub height and rotor diameter for all turbines listed in the EKA budget queue

4.3. Value of the Seismic Impact Limit

Turbines with various powers between 1 MW and 8 MW were modelled to determine the level for the Seismic Impact Limit that would guarantee that the consumption of the 0.2556 nm of budget head-room would result in at least an additional 1 GW of wind capacity. This calculation is based on the worst-case assumption that every additional turbine would produce ground waves with amplitude equal to the Seismic Impact Limit. The hub heights and rotor diameters used in the calculations were those generalised from the turbines power (see section 4.2).

A Seismic Impact Limit of 0.00809 nm.MW$^{-0.5}$ would guarantee an additional 1 GW based on 0.2556 nm of budget head-room (Table 1). The value of the Seismic Impact Limit relative to worse-case installable capacity is independent of wind turbine manufacturer (i.e., 1 GW is guaranteed based on the given assumption whether the EKA Standard algorithm is used, or GE, Nordex, etc.).

Table 1 shows the Seismic Impact Limit calculated for different wind turbine outputs between 1 and 8 MW. The value for Seismic Impact Limit is close to independent to the power (there are small differences at the fifth significant figure). The Equivalent range shown in Table 1 represents the distance at which turbines could be built and with specifically low seismic emissions or systems that have seismic emission reduction technology, i.e., 1000 x 1 MW turbines built 18.9 km from EKA would consume the 0.25560nm of budget head-room, or 125 x 8 MW turbines could be built at 21.34 km. The spectra used to calculate the equivalent range was on the GE turbines measured at Langhope Rig; seismically less impactful turbines (including those with technology that reduces seismic emissions) could be built closer than the ranges shown in Table 1.

The method by which the Seismic Impact Limit was assessed to guarantee 1 GW, was also used to determine levels required for 1.25, 1.5, 2.0 and 2.5 GW. Table 2 lists values for the Seismic Impact Limited required to guarantee these installable capacities. As the total capacity target increases, the Seismic Impact Limit required to guarantee the capacity reduces and the range at which turbines can be installed without seismic mitigation increases.

Turbine Power MW	Hub Height m	Rotor Diameter m	Seismic Impact Limit $nm.MW^{-05}$	Number of Turbines	Equivalent Range km
1	56.4	64.3	0.00809	1000	18.9
2	78.6	90.9	0.00809	500	19.65
3	95.6	111.3	0.00809	333	20.12
3.5	103.0	120.3	0.00809	285	20.31
4	110.0	128.6	0.00809	250	20.47
5	122.6	143.7	0.00809	200	20.75
6	134.0	157.4	0.00809	166	20.98
7	144.5	170.1	0.00808	142	21.18
8	154.3	181.8	0.00809	125	21.34

Table 1 A Seismic Impact Limit 0.00809 $nmMW^{-0.5}$ would guarantee 1000 MW additional capacity based on 0.2556 nm head-room in the EKA budget. A variety of turbines are shown with hub height and rotor diameters based on power output. The number of each turbine that could be installed are shown and the equivalent distance is the range at which the specified turbine could be installed without vibration mitigation (based on the measurement of GE turbines at Langhope Rig).

Target Capacity MW MW	Seismic Impact Limit $nm.MW^{-0.5}$	Equivalent Range for 3.5 MW km
1000	0.00809	20.31
1250	0.00723	21.25
1500	0.00660	22.04
2000	0.00572	23.3
2500	0.00511	24.3

Table 2 Seismic Impact Limits required to guarantee different installable wind energy capacity based on 0.2556 nm head-room in the EKA budget. The equivalent range of 3.5 MW turbines are compared (based on the measurement of GE turbines at Langhope Rig).

5. Installable Capacity

The installable capacity detailed in Section 4.3 assumed the worst-case whereby all new turbines were built close to the EKA and produce seismic levels equal to the Seismic Impact Limit for the given turbine. This implies that turbines are either being built at the exact distance at which they meet the SIL or (more likely) utilise turbines with low seismic emissions which could incorporate some form of seismic reduction technology e.g. isolation whereby they meet the SIL. This worst-case assumption is unlikely; more likely is that many wind farms will be built at further distances from EKA whereby their impact does not approach the Seismic Impact Limit.

To determine how a Seismic Impact Limit may affect the installable capacity within the consultation zone, a simulation was constructed to randomly place wind farms between 10 km and 50 km from EKA (Figure 3). The number of turbines with each wind farm was randomly assigned a number between 1 and 100. The size of each turbine in the farm was randomly assigned a capacity between 1 and 8 MW; and every turbine within any one wind farm had the same capacity. The rotor diameters and hub heights were based on those generalised from the turbine's power as described in Section 4.2. In each simulation, any wind turbines that exceeded the Seismic Impact Limit for its given rated power, the seismic output was limited to equal the Seismic Impact Limit (effectively assuming that the turbine would have sufficiently low seismic emissions to allow it to be built). For each simulation, the total installed capacity was calculated up to the point at which all of the 0.25560 nm of budget head-room was consumed. The simulation was integrated 10,000 times and the probability distribution of total additional installable capacity assessed.

A histogram of additional installable wind power based on setting a limit to guarantee 1 GW is shown in Figure 4. The median distribution of installable capacity of simulations where the Seismic Impact Limit was 0.00809 $nm.MW^{-0.5}$ is 4374 MW (Table 3). Thus, while the Seismic Impact Limit is used to guarantee the installation of 1 GW, the likely installable power is significantly higher. Table 3 also shows the 10th percentile of the distributions; for the Seismic Impact Limit of 0.00809 nm.MW$^{-0.5}$, the 10th percentile is 2694 MW, meaning that in 90% of the simulations the installed capacity was greater than or equal to 2.69 GW. Table 3 lists the median, 10th percentile, and range of installable capacity for Seismic Impact Limits required for 1.25, 1.5, 2.0 and 2.5 GW; in all cases the 10th percentile and median are significantly higher than the targeted minimum levels. Histograms showing the distribution of each targeted minimum levels are shown in Appendix A.

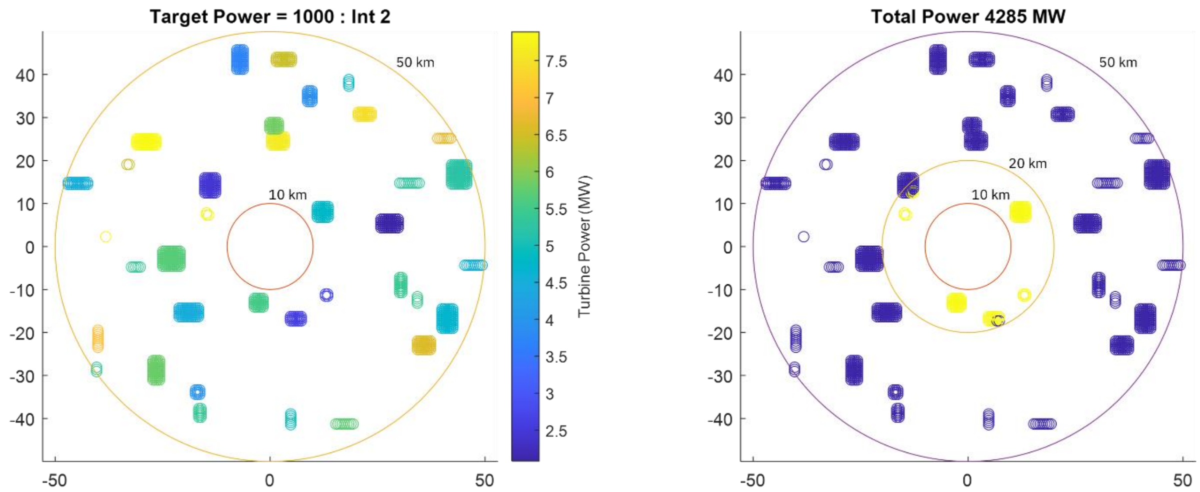


Figure 3 Example of a single iteration. Left: showing the random placement of wind farms that have been assigned turbines with randomised power output (between 2 and 8 MW, see colour bar). Right: Farms coloured blue are below the Seismic Impact Limit, while farms in yellow have their seismic output capped at the Seismic Impact Limit (likely via some form of seismic mitigation).

Target minimum power	Seismic Impact Limits	Median Power	10th Percentile	Median Number of Turbines	Min Power	Max Power
MW	nm.MW$^{-0.5}$	MW	MW		MW	MW
1000	0.00809	4326.8	2677.0	869	1001.0	10603.4
1250	0.00723	4861.9	3227.8	977	1283.5	13396.2
1500	0.00660	5476.5	3784.5	1100	1763.0	12052.0
2000	0.00572	6506.4	4802.9	1309	2341.3	12836.7
2500	0.00511	7495.1	5769.6	1500	3503.5	13619.1

Table 3 Distribution of installable power for different Seismic Impact Limits set to guarantee different installable wind energy capacity based on 0.2556 nm head-room in the EKA budget. The distributions are based on 10,000 randomised simulations for each targeted minimum wind energy capacity.

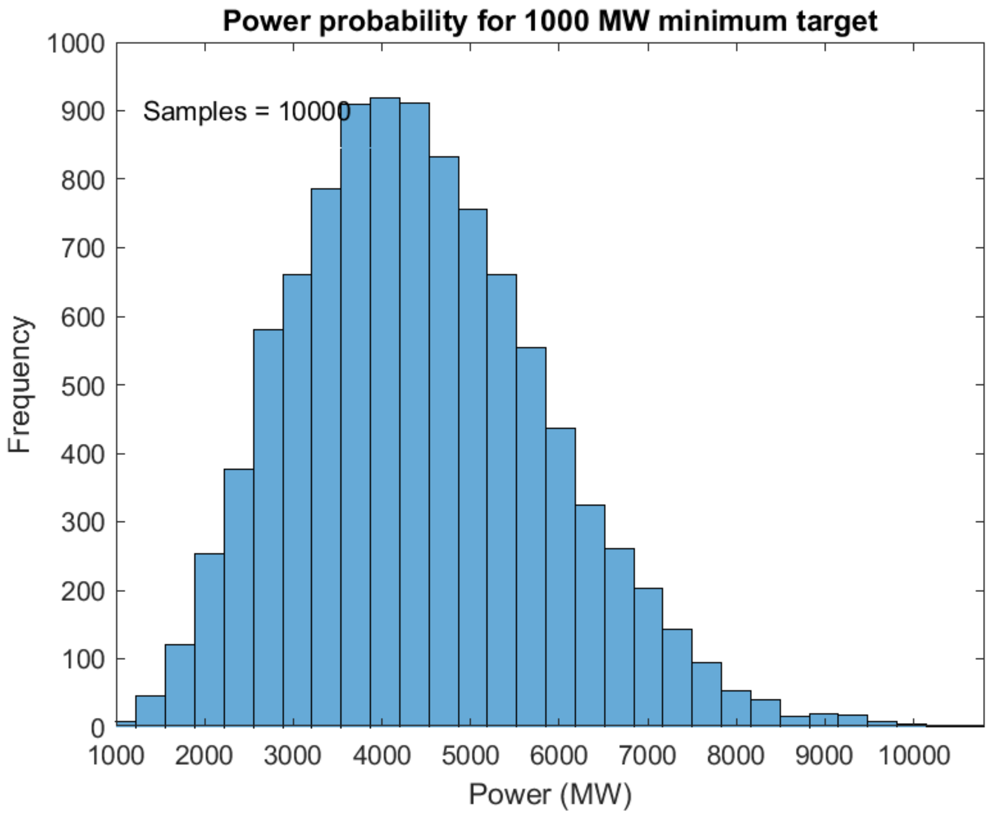


Figure 4 Distribution of additional installed capacity based on setting a Seismic Impact Limit of 0.00809 nm/MW$^{-0.5}$ based on 10,000 randomised simulations. The position, size and capacity of each wind farm was assigned randomly in each iteration of the simulation.

6. Discussion

6.1. Assumptions

The calculation of head-room in the budget was based on the same methodology and assumption set as used in Phase 4 (see Section 6.1 in *Phase 4: Field Audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions* (Ref: SGV_204_Tech_Report_v12 issued 10/2/2022)) and therefore follows the same conversative approach. Here, as in Phase 4, 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. Following this approach, 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.

Continuing to follow a conservative approach, spectra based on the GE turbine at Langhope Rig was used to assess the effective distances (Table 1 and Table 2), and the simulations of the distribution of installable capacity (Table 3). The use of fitted spectra from other turbines measured in Phase 4 would likely result in higher median and 10th percentile figures than those listed in Table 3.

6.2. Implications for future turbines in the consultation zone

The impact of seismic waves from wind turbines on EKA decreases rapidly with distance. Wind turbines built towards the periphery of the consultation zone would not produce seismic amplitudes approaching the Seismic Impact Limit and would therefore not be affected by the setting of a limit.

Wind farms built closer to EKA, (for instance within 18.9km in the case that a 1 MW WTG see Table 1) would be required to demonstrate that the amplitude of seismic waves produced by each turbine do not exceed the Seismic Impact Limit Methods by which this may be demonstrated include, but are not limited to:

- Selection of a turbine make and model with low seismic output, including proof of compliance of the seismic output.
- Wind turbine systems which have been specifically designed to have low seismic emissions.
- Mitigation of seismic levels using physical methods (e.g., damping, isolation, etc).
- Mitigation of seismic levels using non-physical methods (e.g., a control approach).

An advantage of the setting of a Seismic Impact Limit as discussed here, is that developers would be able to specify a value of seismic reduction required to allow the building of wind turbines. With a specified value, developers could assess the cost of mitigation and/or lost yield (in the case of a control-based mitigation strategy) and determine the commercial viability of the proposed wind farm.

6.2.1. Before and after Measurements

It should be noted that this approach does not include further deployable potential within the region if before and after measurements were to be mandated. As described in Phase 4 work, before and after measurements will ultimately optimise the capacity of the consultation zone, whilst continuing to protect the EKA. Were a before and after approach to be adopted this would increase the deployable levels described within this report.

6.2.2. Exclusion Zone Extension

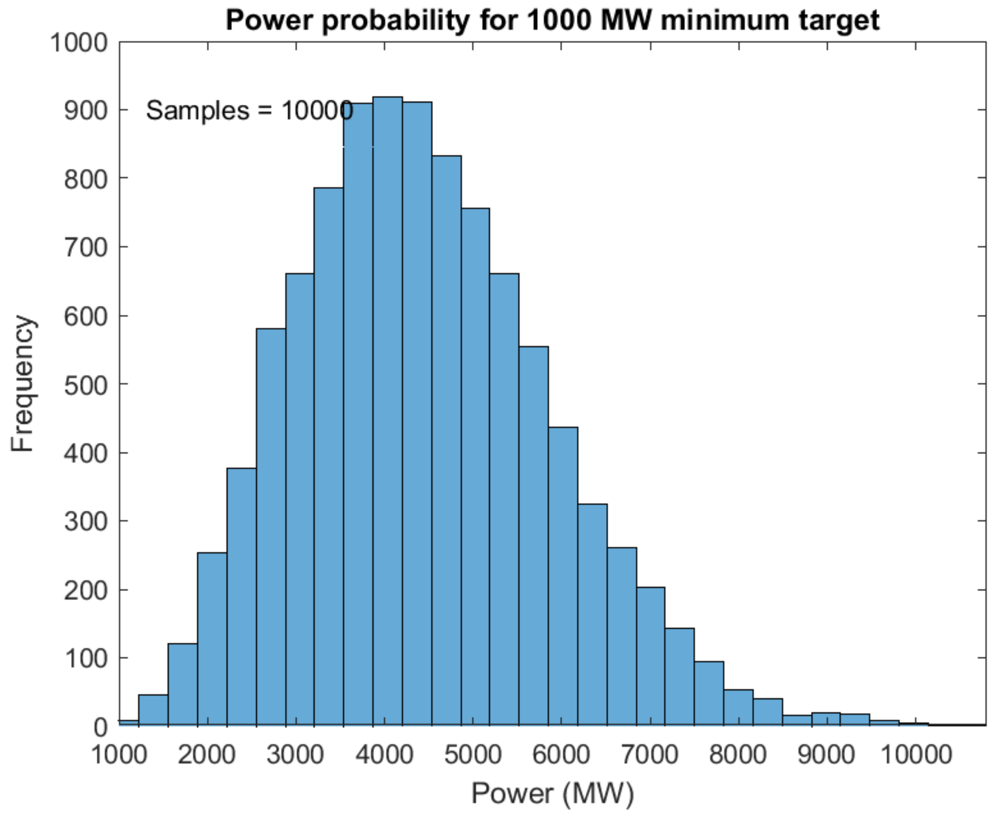
It should be noted that this approach does not include any additional analysis of the potential of increasing the exclusion zone inline with the potential on shore policy options. Increasing the exclusion zone, even with an SIL in place would maintain the minimum level of deployment but increase the potential deployable resource when considering all other metrics used in Table 3, (Median, 10^{th} Percentile, Maximum etc).

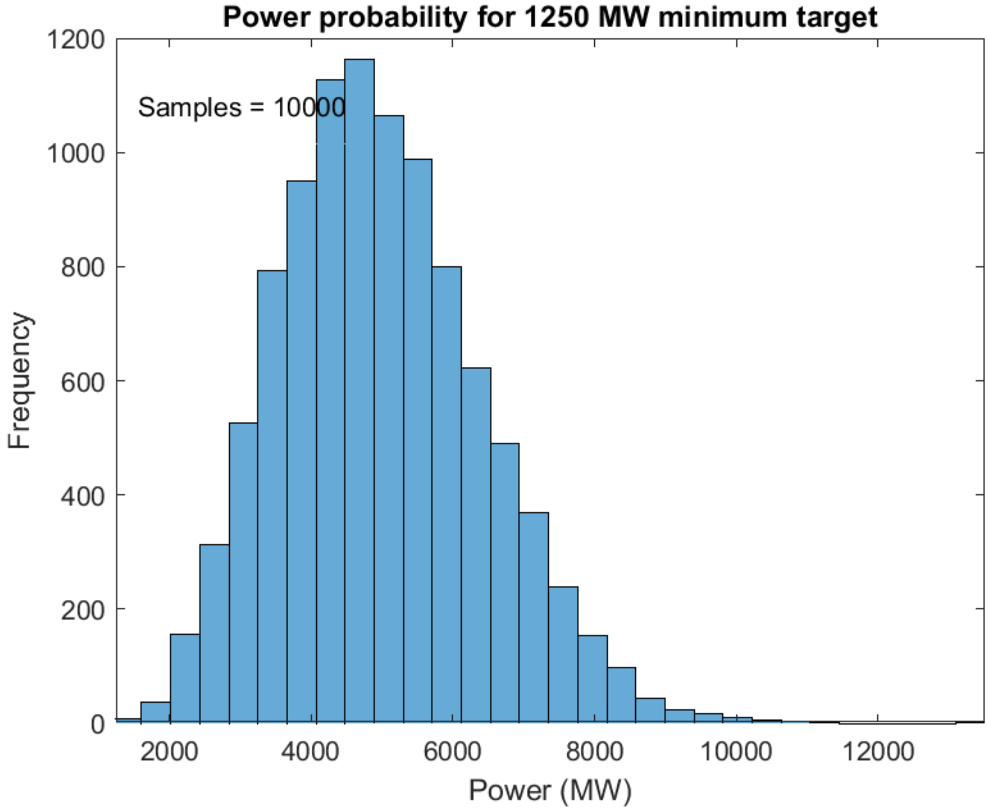
7. Conclusions

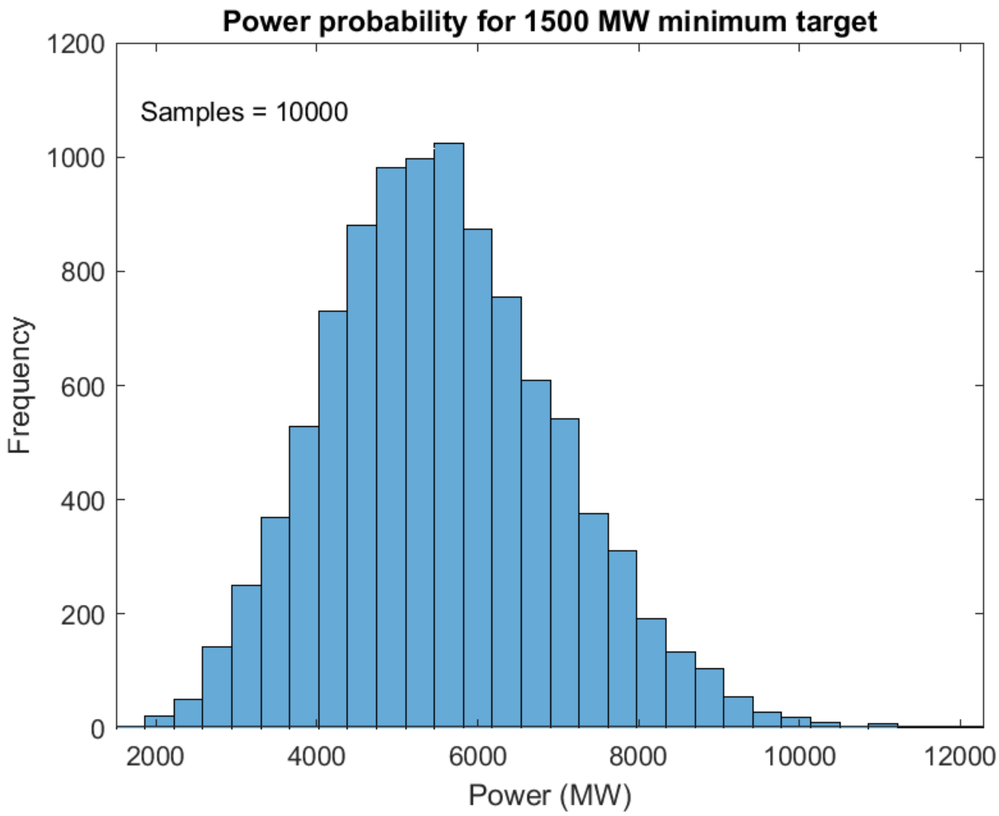
The positions and dimensions of wind turbines in the EKA consultation zone were updated to most accurately represent the state of the Eskdalemuir budget queue at the time of writing (to the author's knowledge). The updated queue was used to assess the head-room in the budget up to and including Scotston Bank wind farm, which was found to be 0.2181 nm. It was determined that a Seismic Impact Limit of 0.00809 nm.$MW^{-0.5}$ would provide 0.2556 nm of head-room and provide at least 1 GW of additional wind capacity in the consultation zone.

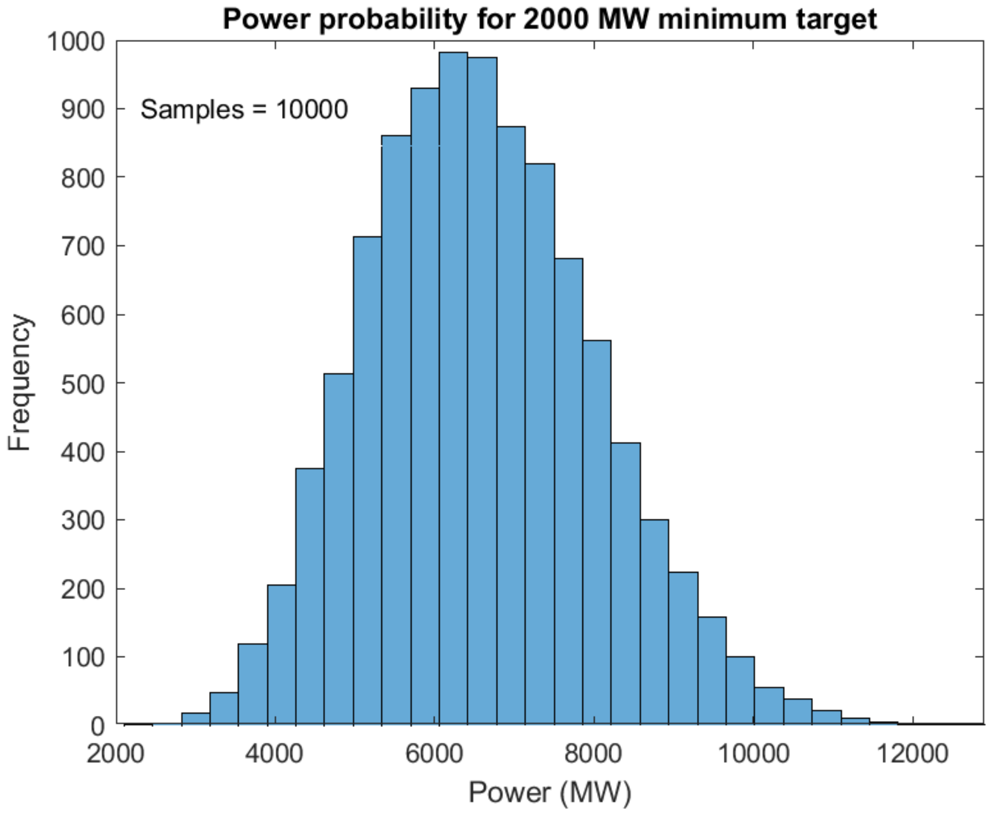
A randomised simulation of wind turbine placement and power was conducted to determine the probability distribution of installable power in the consultation zone. If the 0.2556 nm were consumed by a random distribution of wind turbines with the proviso that they do not exceed the 0.00809 nm.$MW^{-0.5}$ limit, then there is a reasonable expectation that at least 2.7 GW could be installed (10^{th} percentile level), with a median probability of 4.3 GW.

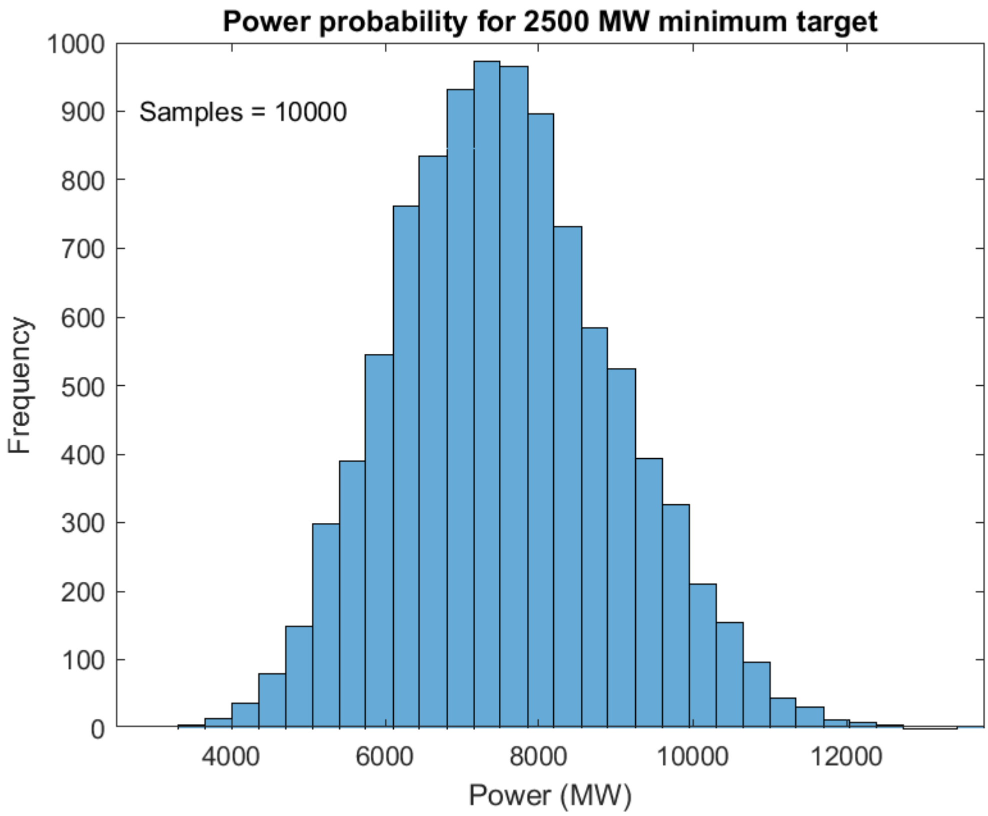
8. Appendix A – Probability distribution of installable capacity for different Seismic Impact Limits




Power probability for 1250 MW minimum target
Samples = 10000
Frequency
0
200
400
600
800
1000
1200
2000
4000
6000
8000
10000
12000
Power (MW)


Power probability for 1500 MW minimum target
Samples = 10000
Frequency
0
200
400
600
800
1000
1200
2000
4000
6000
8000
10000
12000
Power (MW)


Power probability for 2000 MW minimum target
Samples = 10000
Frequency
1000
900
800
700
600
500
400
300
200
100
0
2000
4000
6000
8000
10000
12000
Power (MW)


Power probability for 2500 MW minimum target
Samples = 10000
Frequency
1000
900
800
700
600
500
400
300
200
100
0
4000
6000
8000
10000
12000
Power (MW)

9. Appendix B - EKA Audit Full Queue

Site	Farm	Status	Number Of Turbines	Manufacturer	Spectra Used	Amplitude (nm)	Cumulative Amplitude (nm)
1	Bowbeat	Operational	24	Nordex	Nordex	0.003200	0.003200
2	Carlesgill	Operational	5	Nordex	Enercon	0.022679	0.022904
3	Halkburn - Longpark	Operational	19	Senvion	Senvion	0.004314	0.023307
4	Langhope Rig	Operational	10	GE	GE	0.026837	0.035544
5	Clyde	Operational	152	Siemens	Siemens	0.044432	0.056900
6	Harestanes	Operational	68	Gamesa	Gamesa	0.052477	0.077405
7	Dalswinton	Operational	15	Senvion	Senvion	0.007540	0.077771
8	Minsca	Operational	16	Siemens	Siemens	0.020350	0.080390
9	Carcant	Operational	3	Siemens	Siemens	0.000550	0.080391
10	Ewe Hill	Operational	22	Siemens	Siemens	0.052031	0.095760
11	Andershaw	Operational	11	Vestas	Vestas	0.003640	0.095830
12	Middle Hill - Glenkerie	Operational	11	Vestas	Vestas	0.011317	0.096495
13	Langshaw Farm	Operational	1	unknown	GE	0.000149	0.096496
14	Aikrigg Cottage	Operational	1	unknown	GE	0.000019	0.096496
15	Kingstown Ind Estate	Operational	1	unknown	GE	0.000026	0.096496
16	Lammerlaw Farm 7153	Operational	1	unknown	GE	0.000087	0.096496
17	Brunstock Close	Operational	1	unknown	GE	0.000018	0.096496
18	Minnygap	Operational	10	Nordex	Nordex	0.021684	0.098902
19	Carlesgill Ext	Operational	1	Enercon	Enercon	0.011788	0.099602
20	Land East of Braidwood	Operational	1	unknown	GE	0.000089	0.099602
21	Westmill Farm	Operational	1	unknown	GE	0.000060	0.099602
22	Windyknowe	Operational	1	unknown	GE	0.000037	0.099602
23	Land NW of Ferniehaugh	Operational	2	unknown	GE	0.000061	0.099602
24	Lochmailing	Operational	1	unknown	GE	0.000096	0.099602
25	Threepwood	Operational	1	unknown	GE	0.000067	0.099602

26	Lauder B	Operational	2	unknown	GE	0.000091	0.099602
27	Rennieston Edge	Operational	1	unknown	GE	0.000042	0.099602
28	Meadowside Cottage	Operational	1	unknown	GE	0.000088	0.099602
29	Mosshouses Farm	Operational	1	unknown	GE	0.000063	0.099602
30	Land SW of Larkhill	Operational	1	unknown	GE	0.000063	0.099602
31	Hall Burn	Operational	6	Vestas	Vestas	0.003933	0.099680
32	Muirlea Farm	Operational	2	unknown	GE	0.000139	0.099680
33	Whinney Rig	Operational	1	unknown	GE	0.000328	0.099681
34	Hillfield	Operational	1	unknown	GE	0.000023	0.099681
35	Cargo Farm Cottage	Operational	2	unknown	GE	0.000097	0.099681
36	Land NW of The Batts	Operational	1	unknown	GE	0.000053	0.099681
37	Burnhouse	Operational	1	unknown	GE	0.000060	0.099681
38	The Beeches	Operational	1	unknown	GE	0.000076	0.099681
39	Symington Mains Farm	Operational	1	unknown	GE	0.000074	0.099681
40	Midhill	Operational	1	unknown	GE	0.000093	0.099681
41	Newton of Wiston	Operational	1	unknown	GE	0.000063	0.099681
42	Newtonhead	Operational	1	unknown	GE	0.000113	0.099681
43	Gaups Mill	Operational	1	unknown	GE	0.000030	0.099681
44	South Melbourne Farm	Operational	1	unknown	GE	0.000039	0.099681
45	Walston Braehead Farm	Operational	3	unknown	GE	0.000139	0.099681
46	Easton Farm	Operational	1	unknown	GE	0.000065	0.099681
47	Pumro Fell	Operational	1	unknown	GE	0.000049	0.099681
48	Rivox	Operational	1	unknown	GE	0.000438	0.099682
49	Braco Farm	Operational	2	unknown	GE	0.000065	0.099682
50	Land at Arthurshiels	Operational	1	unknown	GE	0.000085	0.099682
51	Hyndshawland	Operational	1	unknown	GE	0.000095	0.099682
52	Clyde Extension	Operational	54	Siemens	Siemens	0.028526	0.103683
53	East Millrig	Operational	1	unknown	GE	0.000115	0.103683
54	Solwaybank	Operational	15	Vestas	Vestas	0.025924	0.106875
55	Mallshill	Operational	1	unknown	GE	0.000058	0.106875

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56	Middle Muir	Operational	15	Senvion	Senvion	0.004909	0.106988
57	Brockhouse	Operational	1	unknown	GE	0.000062	0.106988
58	Broomhills	Operational	1	unknown	GE	0.000064	0.106988
59	Land SW of Copland Farm	Operational	1	unknown	GE	0.000110	0.106988
60	Land N of Midtown Farm	Operational	1	unknown	GE	0.000100	0.106988
61	Birkenside Farmhouse	Operational	1	unknown	GE	0.000096	0.106988
62	Libberton Mains Farm	Operational	1	unknown	GE	0.000069	0.106988
63	Cloich Forest	Operational	18	EKA Standard	StandardEKA	0.006490	0.107185
64	Bankhouse	Operational	1	unknown	GE	0.000041	0.107185
65	Lammerlaw	Operational	2	unknown	GE	0.000119	0.107185
66	Cormiston Farm	Operational	1	unknown	GE	0.000116	0.107185
67	Hartsop	Operational	1	unknown	GE	0.000097	0.107185
68	Parkhouse Farm	Operational	2	unknown	GE	0.000104	0.107185
69	Shankfield Head	Operational	2	unknown	GE	0.000101	0.107185
70	Cambwell	Operational	1	unknown	GE	0.000131	0.107185
71	South of Hyndfordwells	Operational	3	unknown	GE	0.000141	0.107185
72	Rose Cottage	Operational	1	unknown	GE	0.000033	0.107185
73	Hillend Farm	Operational	1	unknown	GE	0.000133	0.107185
74	Glenkerie Extension	Approved	6	Senvion	Senvion	0.008199	0.107498
75	Deanfoot Farmhouse	Operational	1	unknown	GE	0.000090	0.107498
76	Lion Hill	Approved	4	Vestas	Vestas	0.010068	0.107969
77	West of Hyndfordwells Farm	Operational	1	unknown	GE	0.000058	0.107969
78	Crookedstane Farm	Approved	4	Vestas	Vestas	0.008106	0.108273
79	Windy Edge	Approved	9	EKA Standard	StandardEKA	0.051891	0.120065
80	Blackdyke	Operational	1	unknown	GE	0.000047	0.120065
81	Cottage Farmhouse	Operational	1	unknown	GE	0.000055	0.120065
82	Lampits Farm 2	Operational	1	unknown	GE	0.000158	0.120065

83	Land NW of West Morriston Farm	Operational	1	unknown	GE	0.000118	0.120065
84	Solway re-sub (Beckburn)	Operational	9	Vestas	Vestas	0.005655	0.120199
85	Land East of Mossbank	Operational	2	unknown	GE	0.000138	0.120199
86	Twentyshilling Hill	In Construction	9	EKA Standard	StandardEKA	0.002533	0.120225
87	Townfoot	Operational	1	unknown	GE	0.000090	0.120225
88	South Slipperfield Farmhouse	Operational	1	unknown	GE	0.000094	0.120225
89	Rose Cottage (9812)	Operational	1	unknown	GE	0.000033	0.120225
90	Whitelaw Brae	In Planning	14	EKA Standard	StandardEKA	0.048980	0.129820
91	East of Newton of Covington	Other	2	unknown	GE	0.000100	0.129820
92	Bailey Town Farm	Operational	1	unknown	GE	0.000152	0.129820
93	Kilravoch	Operational	1	unknown	GE	0.000019	0.129820
94	South Melbourne Farm 2	Operational	1	unknown	GE	0.000099	0.129820
95	SW of Kettleshill Farmhouse	Operational	1	unknown	GE	0.000032	0.129820
96	West of M6 Todhills	Operational	1	EWT	GE	0.000467	0.129821
97	Trough Head Farm	Operational	2	unknown	GE	0.000246	0.129821
98	72 Carlisle Road	Operational	2	unknown	GE	0.000253	0.129821
99	Clackmae Farm	Operational	1	unknown	GE	0.000158	0.129821
100	East of Whitslaid Farm	Operational	2	unknown	GE	0.000080	0.129821
101	Crossdykes	In Construction	10	Nordex	Nordex	0.098598	0.163019
102	Whins Farm	Operational	1	unknown	GE	0.000504	0.163019
103	Loganhead	Approved	8	EKA Standard	StandardEKA	0.080087	0.181629
104	Jockstown Farm	Operational	1	unknown	GE	0.000459	0.181630
105	Burnswark Garage	Operational	1	unknown	GE	0.000635	0.181631
106	Wauchope & Newcastleton Forests	S36 planning	90	unknown	GE	0.028080	0.183789

107	North Lowther	S36 planning	30	unknown	GE	0.008890	0.184004
108	Hopsrig	Approved	12	EKA Standard	StandardEKA	0.112423	0.215630
109	Pines Burn	Approved	12	EKA Standard	StandardEKA	0.031084	0.217859
110	Priestgill	Approved	7	EKA Standard	StandardEKA	0.010145	0.218095
111	Land SE of Scotston Bank Farm	Operational	3	unknown	GE	0.000143	0.218095
112	Faw Side	S36 planning	45	unknown	GE	0.385462	0.442884
113	Little Heart Fell	Approved	9	Nordex	Nordex	0.107497	0.455743
114	Twentyshilling hill revised	In Construction	9	unknown	Vestas	0.002933	0.455752
115	Daer	In Scoping	15	unknown	GE	0.036320	0.457197
116	Scoop Hill	In Scoping	78	unknown	GE	0.502472	0.679343
117	Callisterhall	In Scoping	13	Vestas	Vestas	0.073932	0.683354
118	Priestgill resub	In Scoping	7	unknown	Vestas	0.009817	0.683425
119	Westerkirk	In Scoping	20	unknown	GE	0.283812	0.740012
120	Greystone Knowe	In Planning	15	unknown	GE	0.005549	0.740033
121	Loganhead resub	In Planning	8	unknown	Nordex	0.068446	0.743192
122	Hopsrig resub	In Planning	12	unknown	Vestas	0.135103	0.755372
123	Harestanes South	In Planning	8	unknown	GE	0.025899	0.755816
124	Whitelaw resub	In Planning	12	unknown	GE	0.037872	0.756764
125	Scawd Law	In Planning	12	unknown	GE	0.008446	0.756811
126	Grayside	In Planning	25	unknown	GE	0.029194	0.757374
127	Bodinglee	Other	72	unknown	GE	0.015522	0.757533
128	Teviot	Other	62	unknown	GE	0.217989	0.788274
129	West Andershaw	Other	11	unknown	GE	0.005539	0.788293
130	Liitle Gala	In Planning	6	unknown	GE	0.002822	0.788298
131	Windy Edge Resub	Other	12	unknown	GE	0.067342	0.791170