Analysis and independent review of a) the report by Dr. Fabian Limberger and Prof. Dr. Georg Rümpker entitled 'Re-Analysis of seismological data to characterize the decay of ground motions induced by wind turbines' (Sep 2025, 14 p.), b) the report by Michael A. Hasting/HMSC Inc. entitled 'Final Technical Report CWP Eskdalemuir Seismic Station' (May 7, 2025, 39p.), both written for CWP Energy Ltd., and c) commentary of other restrictions applied by the Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO) to any wind turbine development near International Monitoring Stations (IMS) primary or auxiliary stations, pursuant to paragraph 99 of the Operational Manual For Seismological Monitoring And The International Exchange Of Seismological Data, as adopted by the CTBTO.

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Background: The UK Ministry of Defense (MoD) operates the Eskdalemuir (ESK) seismological asset as a so-called 'auxiliary array' forming part of the International Monitoring Station (IMS) network for the Comprehensive Test Ban Treaty Organization (CTBTO). In question is whether the wind turbine (WT) installation (wind farm - WF) operated by CWP Energy interferes with the seismic detection capabilities of ESK. Two separate technical studies, a) and b) above, were provided by CWP Energy as the sole basis of this review.

Executive summary: While WF-induced enhanced ground vibrations can affect the quality of seismic sensors in specific frequency bands, there is no indication that the WF in question causes any detectable noise in the frequency band 2-8 Hz at ESK. Recent achievements by placing sensors in boreholes improved the monitoring conditions at ESK through reduced background noise levels at depth and form an efficient method to keep and even improve the quality standards at ESK in the presence of increasing noise levels at the surface, e.g., through developing reforestation. It is generally acknowledged that the combination of seismic recordings under low-noise conditions (in boreholes of at least several tens of meters) together with using modern data processing methods (including machine-learning techniques) can overcompensate reduction in data quality caused by higher anthropogenic noise levels.

a) Review of the report by Dr. Fabian Limberger and Prof. Dr. Georg Rümpker entitled 'Re-Analysis of seismological data to characterize the decay of ground motions induced by wind turbines' (September 2025, 14 p.):

Besides the overall strongest natural ambient noise peak at about 0.2 Hz - emitted mainly offshore in the North Sea and outside the frequency band of interest here – WTs generate significant energy centered between 1 and 20 Hz through vertically polarized Rayleigh (and to a lesser extent also Love) waves. The WT-induced noise is frequency dependent and decreases with distance from the WT following a power law (e.g., Limberger et al., 2021).

The report by Limberger/Rümpker analyses the 10 surface seismic sensors deployed by CWP in a straight-line profile between the nearest WT and the ESK array with the purpose to quantify how quickly the noise from the WF attenuates towards the array. The report demonstrates that the noise from the WF in the frequency band of interest (2-8 Hz) has completely dissipated by 5 km distance.

Detailed review: The results from the energy-frequency (*'energy' here refers to 'power spectral density - PSD', a common measure of how the power of a signal -here: ground motion noise- is distributed over different frequencies*) plots for the different stations show (their p.4 'Profile Stations') 1. A general decrease in energy with distance (between 300m and 8600 m) across the entire 1-25 Hz frequency band; 2. Consistent energy maxima at 7 distinct frequencies in the frequency band 1-10 Hz (band of primary interest) showing higher energy with increasing wind speed at all stations while the wind speed has substantially decreasing influence with distance, reflecting the decreasing influence of the WF; 3. That the influence of the WF strongly decreases up to 3660 m distance while beyond that distance further noise reduction is small (almost negligible, also documented on p.5 where the stations are plotted together for the wind group 11-12 m/s (strongest wind speed considered here)). Analysis of EKA data with respect to 8660 m distance (p.6) and WT near field (p.7) shows low energy levels, confirming that the WT have no influence on the noise level at EKA in the frequency band 2-8 Hz. Analysis of the day-night difference (p.8) shows a stronger effect at EKA compared to the WT-near field, indicating the continuous elevated noise by the WT observed at short distance. At EKA the stronger day-night difference might be caused by anthropogenic noise being smaller at night. The frequency spectrograms for different stations at wind speed of ~5 m/s (p.9) and ~10m/s (p.10) show comparable noise energy levels at all stations when WT are off while the increased noise energy is strongest close to the WF and decreasing with distance from the WF. This is expected. When WTs are partly off, the observations are largely similar, but not as easy to interpret in detail (p.11). The conclusions of the report are given on p.12 and I concur with each of them. Furthermore, all information and statements given on the remaining p. 2, 3, 13, 14 of the report are sound.

<u>b) Review of the report by Michael A. Hasting/HMSC Inc. entitled 'Final Technical Report CWP Eskdalemuir Seismic Station' (7 May, 2025, 39p.)':</u>

To quantify an expected improvement of signal recordings through reduced background noise levels at seismic stations, sensors can be placed underground in boreholes where noise generally decreases with depth while the improvement in detail depends on local conditions such as e.g., rock formation and also depend on the type of noise (e.g., ambient, electronic). The report by Hasting analyses the recordings from a borehole seismic installation which was implemented with the motivation to quantify an expected improvement of seismic recordings at EKA. This is of interest particularly because of potential WT and forest-induced noise, but also generally to improve the EKA data quality towards continuing fulfilling CTBTO requirements and following earlier steps made in the same direction (e.g., analog-digital transition in 1980s).

CWP had proposed to augment the existing EKA MoD surface array with deep (*here deep presumably refers to few-several hundreds of meter depth*) borehole seismometers to improve detection capability and to mitigate any potential Raleigh waves created by local/regional WFs that propagate towards ESK. To prove concept, CWP commissioned HMSC to install a test borehole of 200 m depth in 2024.

In the report it is concluded that the borehole produces up to a 15 – 25db noise gain against the surface seismometers in the 2–10 Hz passband, and up to a 5-fold increase in signal-to-noise ratio for teleseismic events. I agree with these findings.

Detailed review: In the executive summary, the author states that 'The borehole's performance improves significantly at higher wind velocity as the surface sensors are impacted by noise from the surrounding Eskdalemuir commercial forestry as higher winds blow through the forests creating ground vibrations.' I concur with this conclusion in that the Eskdalemuir commercial forestry is certainly a factor enhancing the noise level at EKA. However, its precise influence is yet to be quantified in detail. The author suggests to install 'a minimum of 10 additional borehole installations of between 30m and 100m, each containing a new 3-component or 1-component borehole seismometer (…). Subject to dialogue with the MoD, it would be possible to expand the upgrade to the remaining 10 sensor locations, which are proposed to be drilled to 30m to 80m and contain a vertical-component sensor in line with the CTBTO requirements. To ensure the best possible array performance, the boreholes sensors are to be cemented in place.' Independent of the site-specific conditions under discussion for EKA due to WFs in the area (see review on Limberger/Rümpker under a.), I concur with the general statement and can state that further seismic borehole installations at EKA complementing surface stations would significantly improve the (CTBTO and beyond) monitoring conditions of the EKA array. This is especially to be expected in the light of additional noise generated e.g., by intensified reforestation activities in the area or other anthropogenic noise. I recommend to cement any downhole sensor into the borehole in the future to achieve best (lowest) possible noise conditions and secure long-term operation under constant conditions. Furthermore, since costs of sensors are typically smaller than drilling costs, I suggest to rather have redundancy in sensors than not cementing the sensors in the borehole (to be able to recover them in case of misfunction) for the sake of best-possible data quality. Consequently, I agree with the statement by the author that installing further borehole sensors at EKA 'will bring EKA up to date with CTBT standards, provide much needed attenuation from existing anthropogenic noise including forestry, agricultural and traffic noise, and afford long-term future proofing, whilst allowing turbines to be built within close proximity to EKA'.

The author states that 'In addition to technical modifications to seismic arrays, recent innovations in mathematical modelling, machine learning and AI are being recognized as valuable new techniques to enhance detection (…). Machine learning denoising autoencoders are in development by CTBTO and Industry to provide crucial tools to filter and clean data which tremendously enhances detection of seismic activity and distinguishes nuclear explosions from other seismic activities'. While I agree that modern methods of data processing, such as e.g., machine-learning based signal detection, can certainly improve the quality of seismic signals to be used, in my opinion the key challenge remains to achieve seismic recordings under lowest possible noise conditions before applying modern processing techniques. This is of particular relevance for EKA (and CTBTO in general) since the frequency band of 'noise' (both natural and anthropogenic) overlaps to a certain extent with the frequency band of interest to CTBTO. In short: Only recordings performed under low-noise conditions (in boreholes) allow for the full benefit of modern data processing methods.

The EKA borehole seismic data since December 2024 show far superior noise levels with respect to surface-based recordings and regularly fall below the 'Peterson (1993) New Low Noise Model (NLNM)' (which is the global standard for quantitatively describing the quality of seismic stations - PSD versus frequency) in low wind speeds. The noise analysis presented in the report follows the state-of-the-art and correctly denotes that the main noise source at the observation site is anthropogenic and cultural noise that 'is caused by wind blowing through the commercial forestry, and agricultural operations'. This confirms results from the Limberger/Rümpker report stating that the effect of the operating WF is not detectable at the EKA site.

The report describes low, middle and high wind days separately. As for high wind days (the ones of primary relevance) it is stated that 'we see the most improvement in the data and … the borehole sensor will outperform any surface sensor.' I agree with this statement. The author states 'that using borehole sensors throughout the (EKA) array will greatly improve the overall data quality, especially on high wind days and high anthropogenic noise levels. The use of borehole sensors will lower the detection threshold and improve the overall capabilities of EKA for not only recording high quality data for seismic events, but also for detection of covert nuclear tests.' I concur with this statement. The author refers to a prominent noise source (4.8 Hz, Fig. 3 in the report) seen at both the surface and downhole sensor. This indeed is a robust (obviously anthropogenic as described due to distinct on-/off-times and seen only during weekdays and working hours) reference signal that is used to demonstrate the overall different performance of surface vs borehole recordings. The author states that 'it is very common for IMS Stations to be upgraded in this fashion and a great number have been supplemented in this way…'. The construction plan of new boreholes at EKA complementing existing surface stations proposed by the author is reasonable but requires an in-depth discussion with MoD.

The author concludes that 'anthropogenic noise that affects the entire Array … is not associated with operations at nearby wind farms'. I concur with this finding. In conclusion, the author has stated correctly in the report that 'the test borehole is very capable of recording background noise well below the Peterson (1993) NLNM and reducing surface noise to a level that mitigates surface noise from any potential wind turbines such that EKA would not be impacted by such development'.

<u>c) Commentary of other restrictions applied by the CTBTO to any wind turbine development near IMS primary or auxiliary stations, pursuant to paragraph 99 of the Operational Manual For Seismological Monitoring And The International Exchange Of Seismological Data, as adopted by the CTBTO</u>.

A full commentary on IMS primary or auxiliary stations worldwide affected by any WF development requires an in-depth review and extended literature search. It is thus beyond the scope of this report. The general requirements for designing, operating and maintaining IMS Stations are set out in 'The Operational Manual For Seismological Monitoring And The International Exchange Of Seismological Data (IMS Manual)'. On top of these general requirements there are national regulations which differ between countries, while specific effects of e.g., WT as relevant for this report are to be handled case by case. Ground motions induced by WT in the lower Hz range can affect seismological measurements up to distances of several kilometers which is evident from both numerical simulations and field measurements of the emitted seismic wave field (see above in section a). Deploying seismic stations in boreholes is known to generally effectively reduce the background noise level over a broad frequency band above 1 Hz with respect to surface installations (e.g., Boese et al., 2015; Malin et al., 2018; Bohnhoff et al., 2018; Zieger & Ritter, 2018; Limberger et al., 2023). The largest signal-to-noise improvement for borehole seismic recordings in the frequency range 1-10 Hz with respect to surface recordings is on the order of 5-10-fold for sensors placed at up 200 m depth (Bohnhoff et al., 2018).

Consequently, monitoring the elastic wave field in shallow (several 10s to few 100s of meters) deep boreholes significantly improves the signal-to-noise ratio in the presence of enhanced natural or anthropogenic noise levels. Given the increasing implementation of noise-sources (e.g., but not limited to reforestation, WFs) it is recommended in general to complement existing seismic surface stations, such as in the frame of CTBTO, by seismometers placed in boreholes. Improved processing techniques are to be used, but their benefit is limited if the noise level at sensors is high.

In conclusion, the impact of seismic noise produced by WTs on seismometers can be decreased if the site-specific distance of several kilometers in general (for specific distance to ESK see a) is kept, or the seismic sensor is installed within a borehole at an adequate depth (minimum several 10s of meters). More precise measures depend on site-specific various geophysical and geological parameters, such as seismic velocities or layering in the subsurface, and should be carefully evaluated for every geological environment separately.

I herewith declare my independence in this matter. I have no commercial interest in the matter, no conflict of interest, no commercial or other relation with either Drs Limberger/Rümpker or HMSC.

(Prof. Dr. Marco Bohnhoff)

Potsdam, November 30, 2025

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