



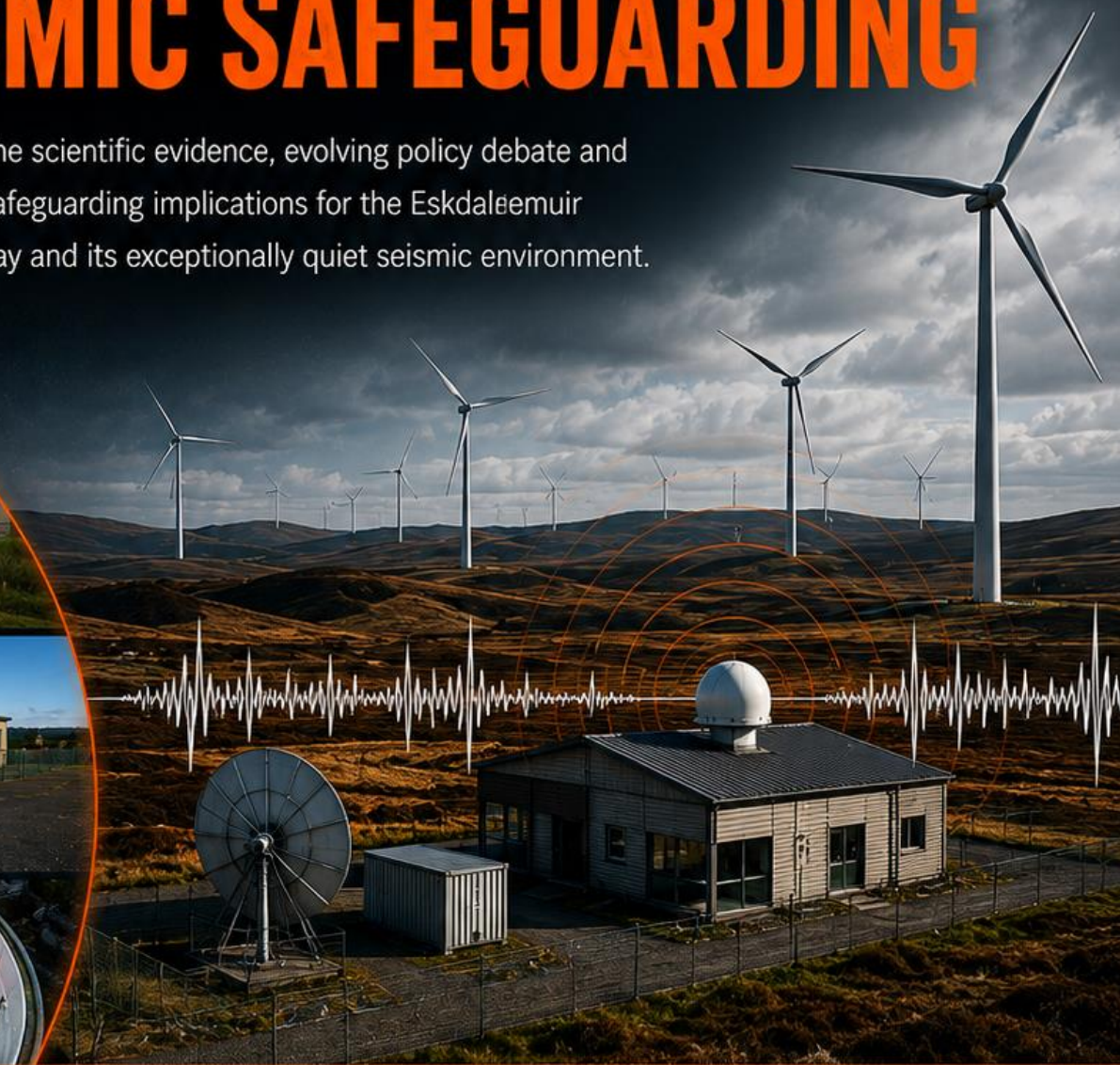
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TECHNICAL REPORT

# ESKDALEMUIR, WIND TURBINES AND SEISMIC SAFEGUARDING

Examining the scientific evidence, evolving policy debate and long-term safeguarding implications for the Eskdalemuir Seismic Array and its exceptionally quiet seismic environment.



**EVIDENCE BASED**

Grounded in peer-reviewed engineering and seismological research.



**PUBLIC INTEREST**

Supporting informed discussion on a matter of national importance.



**TRANSPARENCY**

Reviewing the science, uncertainty and policy proposals.



**PRECAUTION FIRST**

Exploring long-term safeguarding of a unique seismic environment.



**STRATEGIC IMPORTANCE**

Protecting the UK's CTBT monitoring infrastructure.



# Foreword

The Eskdalemuir Seismic Array forms part of the United Kingdom's contribution to the international monitoring infrastructure associated with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The site was originally selected because of its exceptionally quiet seismic environment and its suitability for highly sensitive seismic monitoring.

This report examines the growing debate surrounding large-scale wind turbine development within the wider safeguarding area around Eskdalemuir, particularly in light of the substantial increase in turbine scale since the historic safeguarding framework originally emerged.

## **Drawing upon peer-reviewed engineering and seismological literature, the report examines:**

- turbine-induced seismic ground motion;
- cumulative low-frequency disturbance;
- propagation complexity and uncertainty;
- the long-term preservation of low-noise seismic environments.

The report does not present sensational or exaggerated conclusions. Instead, it considers a precautionary and technically grounded question:

If Eskdalemuir was originally chosen because of its unusually low levels of anthropogenic seismic disturbance, is it prudent to progressively adapt the safeguarding framework to accommodate increasing surrounding industrialisation instead?

The scientific literature reviewed demonstrates that turbine-induced seismic propagation is real, measurable and increasingly complex as turbine infrastructure continues to evolve in scale and structural behaviour.

This report has therefore been prepared as a precautionary technical assessment intended to support informed discussion surrounding the long-term safeguarding of strategically important seismic monitoring infrastructure.

## **ObjectNow**

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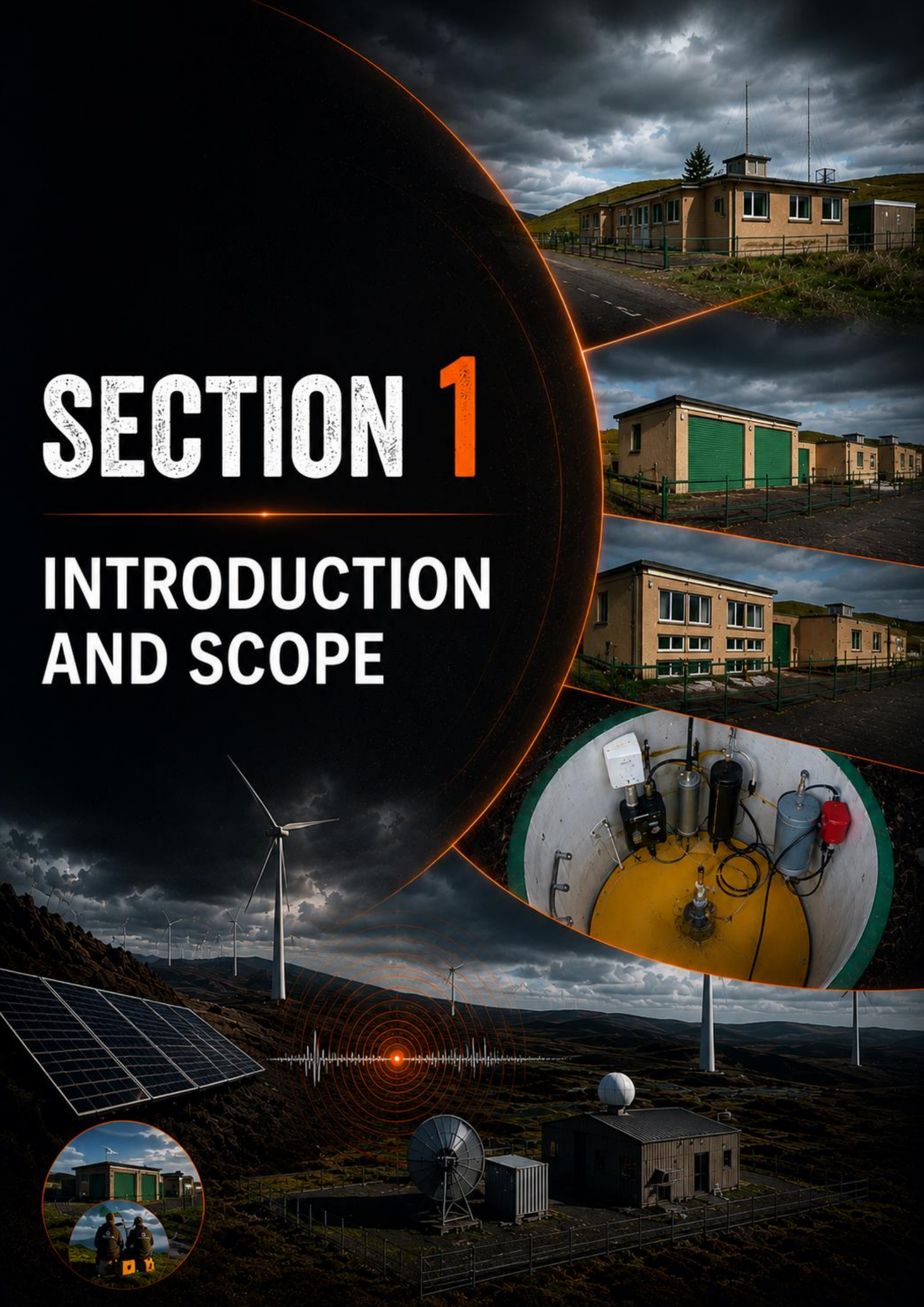
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## **IMPORTANT NOTICE:**

This report is intended as a precautionary technical review examining published scientific literature, evolving turbine scale and long-term safeguarding considerations associated with exceptionally low-noise seismic monitoring environments.

# SECTION 1

## INTRODUCTION AND SCOPE



# 1: Introduction and Scope

- 1.1 The Eskdalemuir Seismic Array (EKA) forms part of the International Monitoring System (IMS) associated with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The purpose of the Array is to assist in the detection and identification of extremely faint low-frequency seismic signals, including signals potentially associated with underground nuclear test activity occurring across large distances. [1]
- 1.2 The Eskdalemuir Array operates within an exceptionally sensitive seismic environment and contributes towards the wider international treaty verification infrastructure associated with nuclear test monitoring obligations. [1]
- 1.3 This report examines the evolving safeguarding debate surrounding wind turbine development within the wider Eskdalemuir consultation and safeguarding area.
- 1.4 Particular regard is given to:
  - turbine-induced seismic ground motion;
  - the increasing scale of modern wind turbines;
  - cumulative low-frequency seismic disturbance;
  - propagation complexity and uncertainty;
  - the long-term preservation of low-noise seismic environments;
  - emerging proposals involving revised safeguarding methodologies and monitoring upgrades.
- 1.5 The report has been prepared as a precautionary technical assessment drawing upon:
  - peer-reviewed engineering and seismological literature;
  - publicly available consultation material;
  - publicly available briefing documents;
  - published safeguarding principles;
  - indicative comparative scaling observations.
- 1.6 This report does not claim to provide:
  - formal Ministry of Defence propagation modelling;
  - definitive exclusion zone calculations;
  - classified operational analysis;
  - formal CTBT performance assessment.
- 1.7 Instead, the report examines whether modern turbine scale, cumulative deployment pressures and evolving safeguarding approaches justify continued precaution surrounding strategically important seismic monitoring infrastructure.
- 1.8 The report is not written from the position that renewable energy development is inherently incompatible with national infrastructure safeguarding. Rather, the report examines whether:
  - historic safeguarding assumptions remain fully representative of modern turbine infrastructure;
  - cumulative long-term effects remain sufficiently understood;
  - precaution continues to be applied appropriately where internationally significant monitoring infrastructure is involved.

- 1.9 Peer-reviewed engineering literature confirms that operating wind turbines generate measurable seismic ground motion capable of being detected by broadband seismometers at distances extending several kilometres from the source turbine. [2][3]
- 1.10 The literature further confirms that:
- turbine-induced seismic behaviour is strongly influenced by structural dynamics and resonance;
  - propagation characteristics are frequency dependent;
  - attenuation behaviour varies according to geology and environmental conditions;
  - cumulative multi-turbine interaction effects are complex and not fully reducible to simplistic fixed-distance assumptions. [2][3]
- 1.11 Importantly, the wider scientific literature also demonstrates that the issue of protection radii surrounding sensitive seismic monitoring infrastructure is already recognised internationally within seismological research. [3]
- 1.12 The report additionally examines the significant evolution in turbine design since the historic Eskdalemuir safeguarding framework originally emerged during the early 2000s.
- 1.13 At the time the historic framework developed, typical UK onshore turbines commonly involved:
- generating capacities of approximately 1–2 MW;
  - blade tip heights commonly below approximately 110 m;
  - materially smaller rotor diameters and structural systems than those now frequently proposed.
- 1.14 Modern onshore turbines now commonly proposed across the United Kingdom frequently involve:
- generating capacities exceeding 6–7 MW;
  - blade tip heights exceeding 200–250 m;
  - substantially larger rotor swept areas;
  - heavier structural and foundation systems;
  - increasingly complex dynamic loading behaviour.
- 1.15 Consequently, one of the central questions examined within this report is whether the assumptions underpinning the historic safeguarding framework remain fully representative of modern turbine infrastructure conditions.
- 1.16 Publicly available material reviewed as part of this assessment further demonstrates that the current policy debate increasingly concerns:
- revised Seismic Impact Limit methodologies;
  - upgraded monitoring systems;
  - borehole sensor installations;
  - revised attenuation assumptions;
  - mitigation approaches intended to permit increased development capacity within the wider safeguarding area.

1.17 The existence of such proposals is not, in itself, improper. It is entirely normal within major infrastructure and planning processes for:

- developers;
- consultants;
- industry bodies;
- Governments;

to commission technical work, advocate revised methodologies and engage in policy discussions concerning infrastructure regulation and economic development.

1.18 However, the reviewed material demonstrates that the current debate is no longer simply about whether turbine-related seismic disturbance exists, as that issue is already recognised within both the safeguarding framework and wider scientific literature.

1.19 The central issue instead concerns:

- acceptable levels of cumulative disturbance;
- how precaution should be applied;
- whether modern turbine scale materially alters historic assumptions;
- whether monitoring systems should be adapted to tolerate increasing surrounding disturbance.

1.20 This report therefore examines the Eskdalemuir safeguarding issue through the combined lenses of:

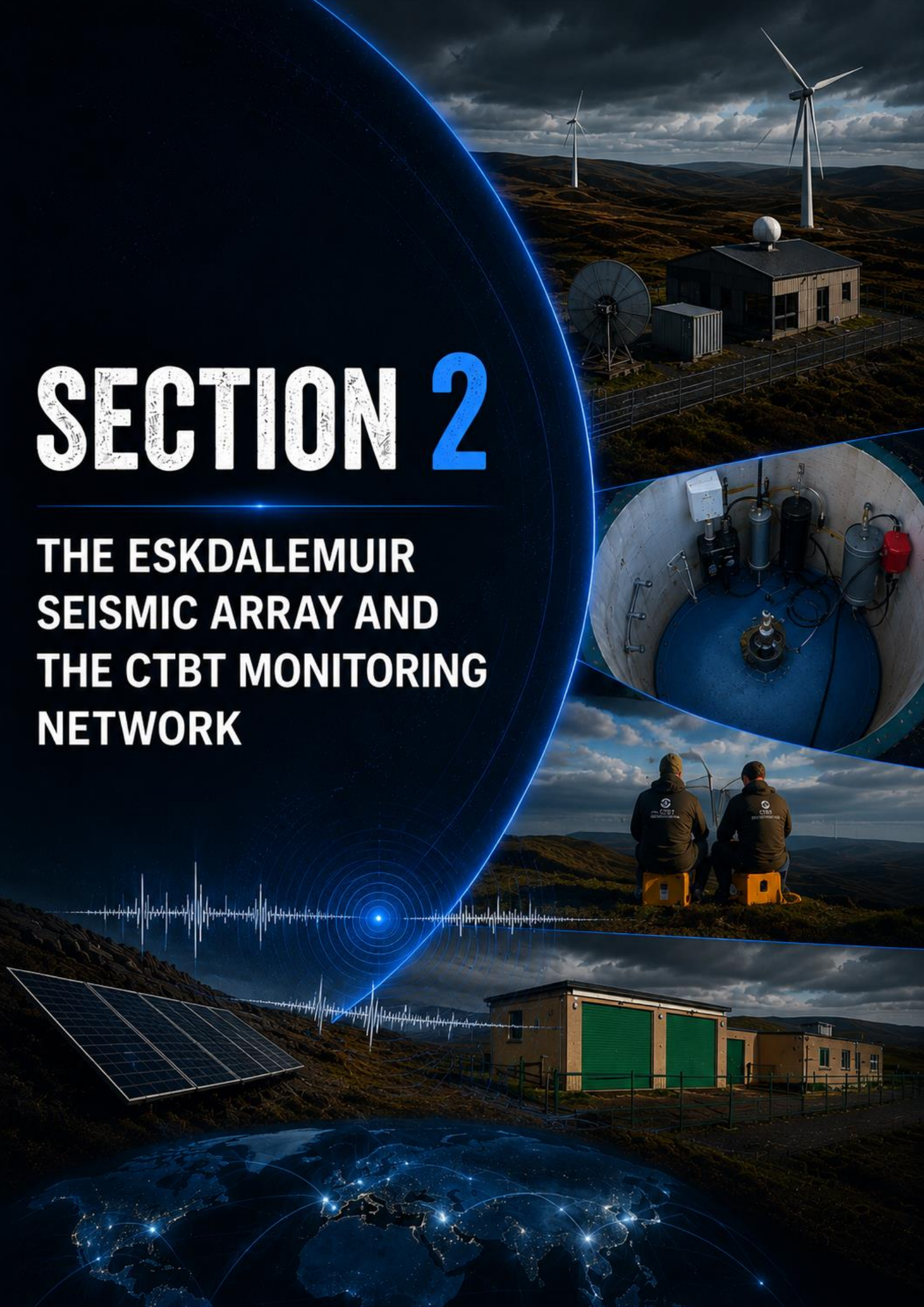
- engineering evidence;
- seismic monitoring principles;
- cumulative uncertainty;
- long-term environmental preservation;
- precautionary infrastructure safeguarding.

## References

- [1] Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), International Monitoring System Overview.
- [2] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.
- [3] Limberger, J., et al. Seismic ground motion induced by wind turbines: Observations, modelling and implications for seismic station protection radii. *Solid Earth*.

# SECTION 2

## THE ESKDALEMUIR SEISMIC ARRAY AND THE CTBT MONITORING NETWORK



## 2: The Eskdalemuir Seismic Array and the CTBT Monitoring Network

- 2.1 The Eskdalemuir Seismic Array forms part of the International Monitoring System (IMS) established under the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The wider IMS network exists to assist in the detection, identification and analysis of nuclear test activity occurring anywhere within the world. [1]
- 2.2 The International Monitoring System consists of several complementary monitoring technologies including:
  - seismic monitoring;
  - hydroacoustic monitoring;
  - infrasound monitoring;
  - radionuclide detection. [1]
- 2.3 Eskdalemuir contributes primarily to the seismic component of that international monitoring infrastructure.
- 2.4 Underground nuclear detonations generate seismic waves which propagate through geological strata over extremely large distances. Those seismic waves can be detected and analysed using highly sensitive seismological instrumentation positioned across the global monitoring network.
- 2.5 The purpose of seismic monitoring within the CTBT framework is not merely to detect large seismic events. The system is specifically designed to identify and characterise extremely faint signals occurring at substantial distances from monitoring stations.
- 2.6 Consequently, seismic monitoring sensitivity becomes critically dependent upon the surrounding background seismic environment.
- 2.7 In practical terms, the quieter the surrounding seismic conditions, the easier it becomes to distinguish weak distant seismic events from persistent background interference.
- 2.8 Seismic monitoring capability is therefore not determined solely by the quality of the instrumentation itself. It also depends heavily upon preserving low levels of surrounding anthropogenic seismic disturbance.
- 2.9 This principle is well recognised within the scientific literature.
- 2.10 Limberger et al. explicitly note that protection radii are applied around sensitive seismological stations due to concerns regarding turbine-induced seismic interference affecting the quality of seismic recordings. [2]
- 2.11 Similarly, Nagel et al. confirm that seismic monitoring stations are intentionally located within environments containing minimal disruptive influences because of the sensitivity of the instrumentation involved. [3]

- 2.12 The Eskdalemuir site was therefore not selected arbitrarily. The location was chosen because it provided:
- low levels of anthropogenic seismic disturbance;
  - limited industrial vibration;
  - relatively stable geological conditions;
  - exceptionally quiet background seismic characteristics suitable for sensitive monitoring operations.
- 2.13 The surrounding environmental conditions formed part of the operational suitability of the site itself.
- 2.14 This distinction is important because the safeguarding debate surrounding Eskdalemuir is often misunderstood.
- 2.15 The issue is not whether wind turbines somehow replicate nuclear explosions. Nor is the issue whether the monitoring system would suddenly cease functioning entirely if turbines were constructed within the wider area.
- 2.16 Rather, the concern relates to whether cumulative low-frequency anthropogenic vibration may progressively elevate the surrounding seismic noise environment against which faint seismic signals must be identified.
- 2.17 The relevant operational issue therefore concerns:
- signal-to-noise ratio;
  - background seismic elevation;
  - cumulative disturbance;
  - sensitivity reduction;
  - long-term degradation of exceptionally quiet monitoring conditions.
- 2.18 Such effects may emerge gradually rather than through immediate or catastrophic operational failure.
- 2.19 This distinction is particularly important within seismic monitoring because:
- stronger seismic events may remain detectable;
  - the monitoring system may continue functioning overall;
  - cumulative background elevation may nevertheless reduce sensitivity to weaker signals.
- 2.20 The scientific literature additionally demonstrates that wind turbine induced seismic behaviour is not merely theoretical.
- 2.21 Nagel et al. confirm that operating turbines generate measurable seismic ground motion detectable by broadband seismometers at distances extending several kilometres from source turbines. [3]
- 2.22 Limberger et al. further demonstrate that lower-frequency turbine-induced seismic peaks remained detectable at the furthest measurement points within their study profile and that propagation behaviour is strongly influenced by frequency and geology. [2]

2.23 These findings are important because they demonstrate that:

- turbine-induced seismic propagation is real;
- propagation behaviour is complex;
- attenuation characteristics vary;
- cumulative interaction effects require careful consideration.

2.24 The wider safeguarding issue surrounding Eskdalemuir therefore concerns not whether measurable turbine-induced seismic disturbance exists, but rather:

- what level of cumulative disturbance is acceptable;
- how uncertainty should be managed;
- whether modern turbine infrastructure remains compatible with preserving exceptionally quiet seismic conditions surrounding strategically important monitoring infrastructure.

2.25 This issue becomes particularly important given the substantial increase in modern turbine scale relative to the infrastructure assumptions that existed when the historic Eskdalemuir safeguarding framework originally emerged.

## References

- [1] Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), International Monitoring System Overview.
- [2] Limberger, J., et al. Seismic ground motion induced by wind turbines: Observations, modelling and implications for seismic station protection radii. *Solid Earth*.
- [3] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.

# SECTION 3

## HISTORICAL DEVELOPMENT OF THE ESKDALEMUIR SAFEGUARDING FRAMEWORK



### 3: Historical Development of the Eskdalemuir Safeguarding Framework

- 3.1 The safeguarding arrangements surrounding the Eskdalemuir Seismic Array emerged during the early expansion of commercial onshore wind development within the United Kingdom during the late 1990s and early 2000s.
- 3.2 As wind turbine deployment increased, concerns began to emerge regarding the potential interaction between turbine-induced seismic vibration and the exceptionally sensitive monitoring environment surrounding the Eskdalemuir Array.
- 3.3 The resulting safeguarding framework recognised that:
  - operating wind turbines generate measurable low-frequency seismic disturbance;
  - such disturbance may propagate through geological strata over considerable distances;
  - cumulative interaction effects required precautionary assessment.
- 3.4 Consequently, a safeguarding and consultation structure developed around the Array incorporating:
  - a central exclusion area;
  - a wider 50 km consultation and safeguarding radius;
  - cumulative Seismic Impact Limit (SIL) assessment procedures overseen by the Ministry of Defence.
- 3.5 The existence of this framework is itself important because it demonstrates that turbine-related seismic interaction was already considered sufficiently credible and operationally relevant to justify formal safeguarding measures.
- 3.6 Importantly, the historic framework was developed during a materially different phase of turbine engineering and commercial deployment.
- 3.7 During the early 2000s, typical UK onshore turbines commonly involved:
  - generating capacities between approximately 1 MW and 2 MW;
  - blade tip heights commonly below approximately 100–110 m;
  - materially smaller rotor swept areas;
  - lighter nacelle assemblies;
  - smaller tower structures and foundations.
- 3.8 At that stage of turbine development, most commercial turbines remained significantly smaller than the modern infrastructure now commonly proposed within contemporary UK wind farm applications.
- 3.9 This distinction is highly important because the original safeguarding assumptions emerged within the context of those earlier turbine characteristics.
- 3.10 Since that period, turbine technology has evolved substantially.

- 3.11 Modern onshore turbines now frequently involve:
- generating capacities exceeding 6–7 MW;
  - blade tip heights exceeding 200–250 m;
  - substantially larger rotor diameters;
  - heavier rotating masses;
  - larger reinforced concrete foundations;
  - increasingly flexible tower structures.
- 3.12 Consequently, modern turbines are not directly comparable to the infrastructure assumptions underpinning the original safeguarding framework.
- 3.13 The peer-reviewed engineering literature demonstrates that turbine-induced seismic behaviour is strongly influenced by:
- structural dynamics;
  - resonance behaviour;
  - tower flexibility;
  - excitation frequencies;
  - foundation interaction;
  - operational loading conditions. [1]
- 3.14 The Nagel et al. study specifically explains that larger turbines increasingly utilise “soft-stiff” and “soft-soft” structural design approaches because traditional “stiff-stiff” tower concepts become economically impractical at larger scales. [1]
- 3.15 These modern design approaches involve increasingly complex dynamic behaviour associated with:
- tower bending frequencies;
  - resonance interaction;
  - cyclic aerodynamic loading;
  - rotor excitation frequencies.
- 3.16 The study additionally explains that larger turbines frequently pass through resonance conditions during operation due to the relationship between natural structural frequencies and rotational excitation frequencies. [1]
- 3.17 These findings are highly relevant to the Eskdalemuir safeguarding issue because they demonstrate that modern turbines are dynamically more complex than earlier turbine generations around which the historic safeguarding framework was originally developed.
- 3.18 The current policy debate therefore does not exist within the same engineering context as that which existed when the original safeguarding assumptions emerged.
- 3.19 This issue is further reflected within the continuing Government consultation regarding revised Eskdalemuir Seismic Impact Limits and safeguarding methodologies.
- 3.20 The existence of the consultation itself demonstrates that:
- the safeguarding issue remains active;
  - the historic framework is undergoing reassessment;
  - competing technical approaches continue to exist regarding how turbine-related seismic effects should be assessed and managed.

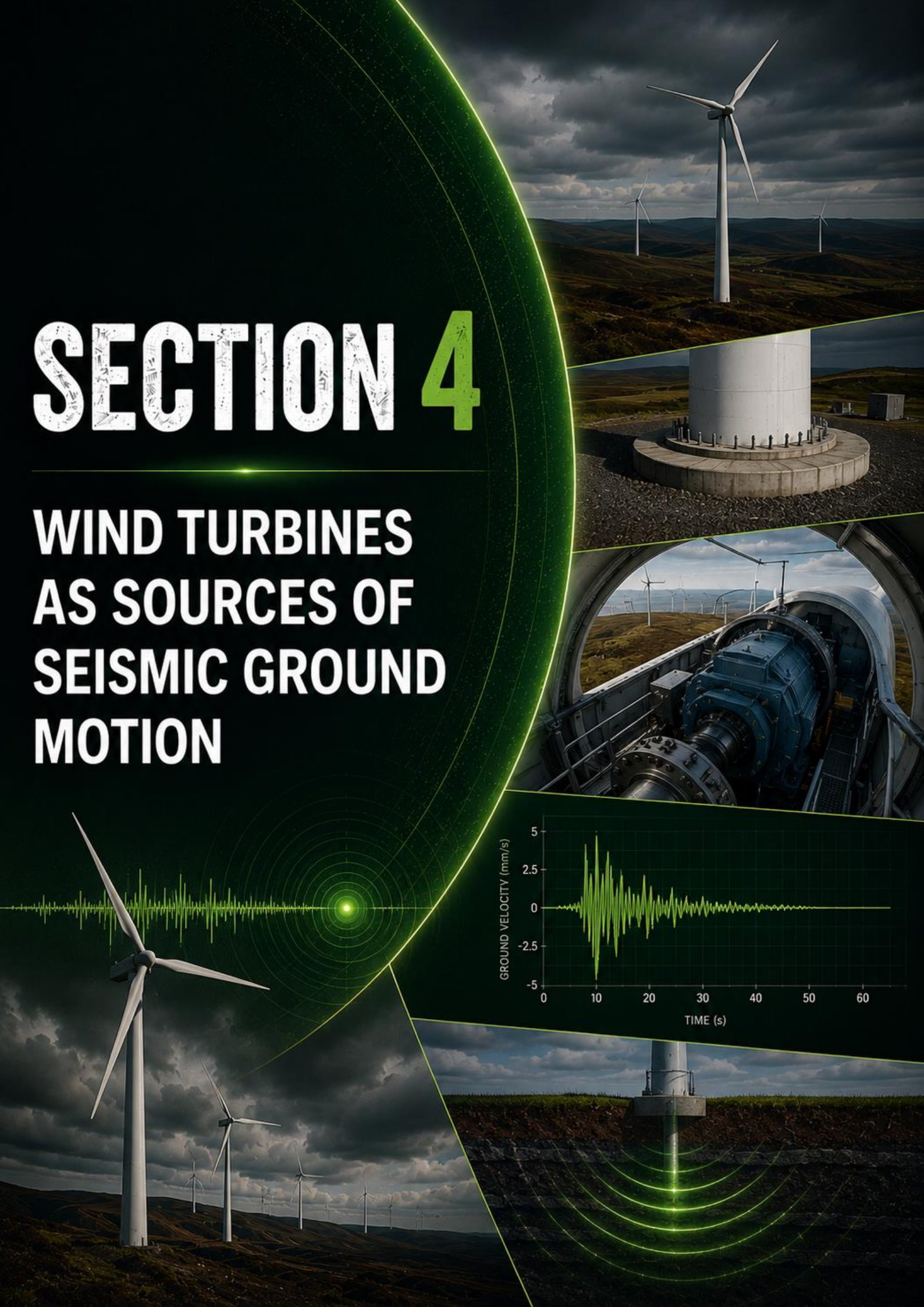
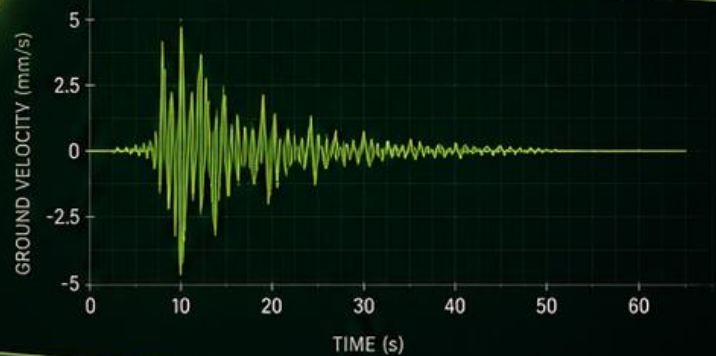
- 3.21 Importantly, the current debate does not concern whether measurable turbine-induced seismic disturbance exists. That issue is already recognised within:
- the historic safeguarding framework;
  - the scientific literature;
  - the consultation process itself. [1][2]
- 3.22 Instead, the present debate concerns:
- how cumulative impacts should be interpreted;
  - whether historic assumptions remain representative of modern infrastructure;
  - how precaution should be applied;
  - whether revised methodologies and mitigation systems justify increased development capacity within the wider safeguarding area.
- 3.23 Publicly available briefing material reviewed as part of this assessment additionally indicates that some developers and consultants advocate revised safeguarding approaches involving:
- upgraded borehole monitoring systems;
  - revised attenuation modelling;
  - revised cumulative assessment methodologies;
  - expanded development capacity within the wider consultation area.
- 3.24 The existence of such proposals is not improper. It is entirely normal within major infrastructure sectors for:
- developers;
  - consultants;
  - industry bodies;
  - Governments;
- to explore revised technical methodologies and mitigation approaches where substantial infrastructure and economic interests are involved.
- 3.25 However, the evolution of these proposals demonstrates a potentially significant shift in safeguarding philosophy.
- 3.26 Historically, the safeguarding framework focused primarily upon preserving the naturally quiet seismic environment surrounding the Array itself.
- 3.27 Some more recent proposals increasingly focus upon adapting monitoring systems and mitigation methodologies in order to accommodate increasing surrounding anthropogenic disturbance.
- 3.28 This distinction forms one of the central precautionary issues examined within this report.

## References

- [1] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.
- [2] UK Government Consultation on Eskdalemuir Seismic Impact Limits and Safeguarding Arrangements, 2026.

# SECTION 4

## WIND TURBINES AS SOURCES OF SEISMIC GROUND MOTION



## 4: Wind Turbines as Sources of Seismic Ground Motion

- 4.1 Modern wind turbines are large rotating mechanical systems which continuously transfer dynamic loading forces into the surrounding ground environment during operation.
- 4.2 These forces arise through the interaction of:
- rotating rotor assemblies;
  - aerodynamic loading;
  - tower flexibility;
  - drivetrain behaviour;
  - structural resonance;
  - foundation-ground coupling.
- 4.3 The resulting vibration energy propagates through the turbine structure into the foundations and subsequently into surrounding geological strata as measurable seismic ground motion.
- 4.4 The existence of turbine-induced seismic vibration is well established within peer-reviewed engineering and seismological literature.
- 4.5 Nagel et al. explicitly state that:
- “The resulting vibrations, generated at the upper end of the tower, are modified by the dynamic properties of the tower structure and pass through the foundations into the ground.” [1]
- 4.6 The same study further confirms that:
- “Broadband seismometers record these ground vibrations not only directly adjacent to the wind turbine but also at greater distances of (up to) several kilometres from the turbine.” [1]
- 4.7 Importantly, the paper demonstrates that turbine-induced seismic behaviour is not governed simply by turbine rotation alone.
- 4.8 Instead, the dominant behaviour arises from complex structural dynamics involving:
- tower resonance;
  - bending frequencies;
  - aerodynamic excitation;
  - rotor excitation frequencies;
  - structural stiffness;
  - modal response characteristics.
- 4.9 Nagel et al. specifically conclude that:
- “The structural properties of the tower structure significantly influence the type and intensity of the vibrations induced in the ground and dominate the ground motion amplitudes.” [1]
- 4.10 This finding is particularly important because it demonstrates that turbine-induced seismic behaviour depends heavily upon the structural design of the turbine itself.

- 4.11 The study explains that larger turbines increasingly adopt:
- “soft-stiff”;
- and in some cases:
- “soft-soft”;
- tower design approaches due to economic and engineering limitations associated with very large structures. [1]
- 4.12 These approaches involve intentionally more flexible tower behaviour compared with earlier smaller turbine generations.
- 4.13 As turbine dimensions increase, the interaction between:
- structural flexibility;
  - natural frequencies;
  - aerodynamic loading;
  - rotational excitation frequencies;
- becomes increasingly important.
- 4.14 The study explains that resonance conditions must be carefully managed because turbine operation may pass through excitation frequencies associated with natural structural frequencies during operation. [1]
- 4.15 This dynamic behaviour creates complex vibration patterns which cannot be reduced to simplistic assumptions based solely upon turbine height or rotational speed.
- 4.16 Wind turbine induced seismic signals are additionally frequency dependent.
- 4.17 Limberger et al. identified multiple distinct seismic frequency peaks associated with turbine operation, including detectable peaks within the 1–8 Hz frequency range. [2]
- 4.18 The same study observed that:
- lower frequency signals propagated over greater distances;
  - attenuation behaviour varied significantly by frequency;
  - multiple turbines produced interacting seismic wave fields. [2]
- 4.19 This distinction is important because lower-frequency seismic waves generally attenuate more slowly than higher-frequency vibration.
- 4.20 Consequently, low-frequency turbine-induced ground motion may remain detectable over substantially larger distances depending upon:
- geology;
  - environmental conditions;
  - turbine configuration;
  - cumulative turbine interaction.
- 4.21 Limberger et al. additionally identified that multiple turbines create interacting seismic radiation patterns through wave interference effects. [2]

- 4.22 The study specifically states:
- “Phase differences between source signals have significant effects on the seismic radiation pattern and amplitude decays.” [2]
- 4.23 This finding is highly significant because it demonstrates that cumulative multi-turbine interaction effects are dynamically complex and cannot necessarily be simplified into uniform fixed-distance assumptions.
- 4.24 The literature further demonstrates that geological conditions exert major influence over propagation behaviour.
- 4.25 Limberger et al. observed that attenuation behaviour varied according to:
- seismic shear wave velocity;
  - subsurface geology;
  - quality factors within geological layers;
  - surface wave propagation characteristics. [2]
- 4.26 Similarly, Nagel et al. note that:
- foundation behaviour;
  - local geology;
  - tower structural dynamics;
  - damping behaviour;
- all influence seismic propagation and measured ground amplitudes. [1]
- 4.27 These findings are important because they demonstrate that turbine-induced seismic propagation is:
- site dependent;
  - frequency dependent;
  - structurally dependent;
  - influenced by cumulative interaction effects.
- 4.28 Consequently, simplistic assumptions that seismic impacts can always be represented using uniform attenuation distances may not fully reflect the complexity identified within the scientific literature.
- 4.29 The literature also demonstrates that turbine-induced seismic vibration is measurable under normal operating conditions rather than only during exceptional operational events.
- 4.30 Nagel et al. observed that operational turbines generated vibration amplitudes several orders of magnitude greater than measurements taken when the turbines were not operating. [1]
- 4.31 Limberger et al. similarly demonstrated that distinct seismic frequency peaks disappeared when turbines were in low or non-operational states. [2]
- 4.32 These observations confirm that the measured seismic effects were directly associated with turbine operation itself rather than unrelated environmental background conditions.
- 4.33 Importantly, none of the reviewed literature suggests that turbine-induced seismic waves are equivalent to nuclear explosion signals.

4.34 Rather, the safeguarding concern relates to:

- cumulative background seismic elevation;
- persistent low-frequency interference;
- degradation of exceptionally quiet monitoring conditions;
- reduced signal discrimination capability within sensitive seismic environments.

4.35 The scientific literature therefore supports several important conclusions relevant to the Eskdalemuir safeguarding debate:

- turbine-induced seismic propagation is real;
- propagation behaviour is complex;
- structural dynamics matter significantly;
- cumulative interaction effects are important;
- attenuation behaviour is variable rather than uniform;
- lower-frequency signals may propagate over substantial distances.

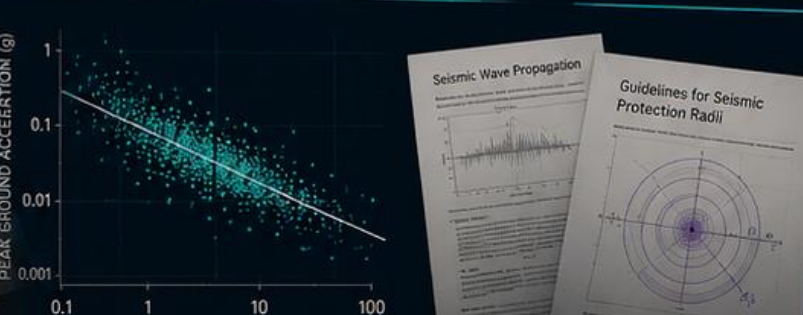
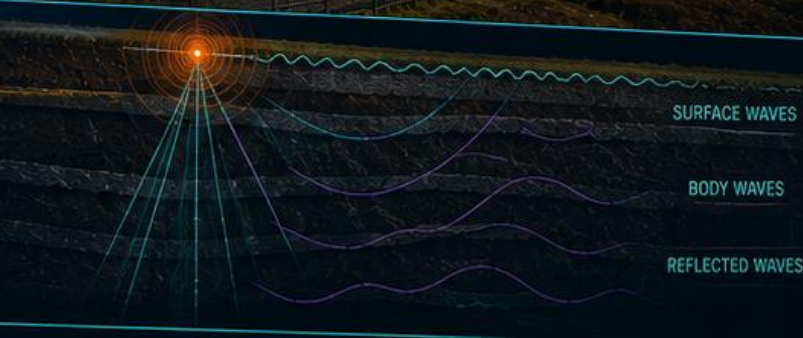
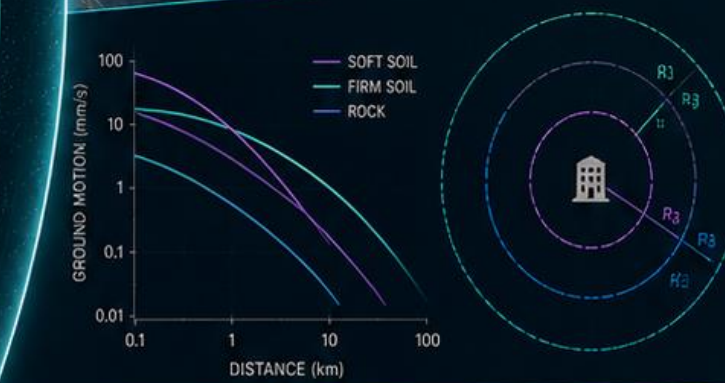
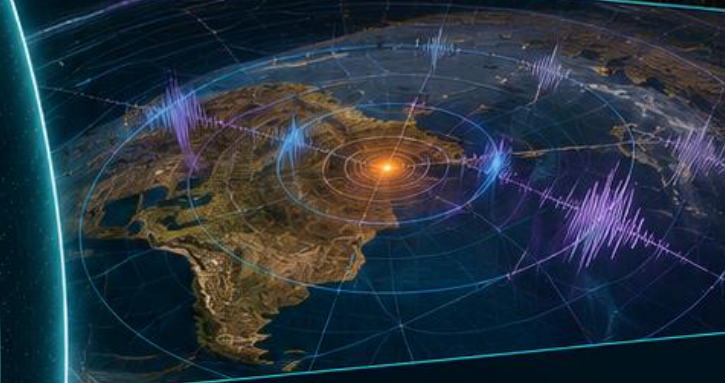
4.36 These findings form an important technical foundation for understanding why safeguarding concerns surrounding exceptionally sensitive seismic monitoring environments continue to remain operationally relevant.

## References

- [1] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.
- [2] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.

# SECTION 5

## SCIENTIFIC LITERATURE RELATING TO SEISMIC PROPAGATION AND PROTECTION RADII



## 5: Scientific Literature Relating to Seismic Propagation and Protection Radii

- 5.1 Research into turbine-induced seismic propagation has expanded significantly over the past two decades as wind turbine deployment has increased near sensitive seismic monitoring infrastructure.
- 5.2 The scientific literature now consistently demonstrates that operating wind turbines generate measurable seismic ground motion capable of propagating through geological strata and being detected by sensitive seismic instrumentation.
- 5.3 Importantly, the literature additionally demonstrates that:
  - propagation behaviour is frequency dependent;
  - attenuation characteristics vary according to geology;
  - cumulative turbine interaction effects are significant;
  - seismic protection radii are an established scientific consideration around sensitive monitoring stations.
- 5.4 One of the earliest widely referenced studies within this field was undertaken by Styles et al. (2005), which examined the relationship between wind turbine activity and seismic disturbance affecting nearby monitoring infrastructure.
- 5.5 The study identified discrete frequency peaks associated with wind turbine operation and highlighted concerns regarding interference with seismic monitoring environments.
- 5.6 Subsequent studies expanded upon this work and increasingly demonstrated that turbine-induced seismic effects extend beyond immediate local turbine foundations.
- 5.7 Saccorotti et al. (2011) identified seismic signals associated with wind turbines at distances extending up to approximately 11 km from source installations. [1]
- 5.8 Friedrich et al. (2018) demonstrated that seismic analysis techniques could distinguish between different wind farms based upon differences in frequency content and propagation behaviour. [2]
- 5.9 Westwood and Styles (2017) identified that Rayleigh waves dominate much of the seismic wave field emitted by wind turbines. [3]
- 5.10 This finding was subsequently supported by numerical simulation work undertaken by Gortsas et al. (2017). [4]
- 5.11 The significance of these findings is that turbine-induced seismic waves do not propagate randomly or uniformly. Instead, wave behaviour depends upon:
  - wave type;
  - frequency characteristics;
  - geological conditions;
  - structural resonance behaviour;
  - interaction between multiple turbine sources.

- 5.12 Limberger et al. provide particularly important findings relevant to the Eskdalemuir safeguarding debate because the study directly examines:
- amplitude decay behaviour;
  - frequency dependence;
  - analytical modelling;
  - implications for seismic station protection radii. [5]
- 5.13 The study observed multiple distinct seismic frequency peaks associated with turbine operation between approximately 1 Hz and 8 Hz. [5]
- 5.14 Importantly, the authors observed that:
- lower-frequency signals propagated substantially further than higher-frequency signals;
  - identifiable lower-frequency peaks remained detectable at the furthest measurement locations within the study profile. [5]
- 5.15 The study additionally demonstrated that attenuation behaviour varied significantly according to frequency.
- 5.16 The measured attenuation factors ranged from:
- relatively weak attenuation at lower frequencies;
  - to:
  - substantially stronger attenuation at higher frequencies. [5]
- 5.17 These findings are highly significant because they demonstrate that low-frequency turbine-induced seismic energy may persist over materially greater distances than higher-frequency vibration.
- 5.18 Limberger et al. additionally observed that multiple turbines generated interacting seismic wave fields rather than isolated independent signals. [5]
- 5.19 The study explicitly states:
- “Phase differences between source signals have significant effects on the seismic radiation pattern and amplitude decays.” [5]
- 5.20 This finding is particularly important because it demonstrates that cumulative propagation behaviour may become increasingly complex as turbine numbers increase.
- 5.21 The study further concludes that seismic radiation patterns depend significantly upon:
- turbine geometry;
  - source interaction;
  - wave interference behaviour;
  - geological conditions;
  - attenuation characteristics.
- 5.22 Limberger et al. additionally discuss the use of protection radii around sensitive seismic stations and reference previous work proposing specific safeguarding distances associated with seismological observatories. [5]

- 5.23 This is important because it demonstrates that the concept of applying precautionary separation distances around sensitive seismic monitoring infrastructure is already established within the wider scientific literature.
- 5.24 Nagel et al. provide further important findings concerning the structural and engineering behaviour underlying turbine-induced seismic propagation.
- 5.25 The study explains that:
- modern wind turbines are dynamically complex systems;
  - structural flexibility significantly influences vibration behaviour;
  - tower resonance and natural frequencies materially affect ground motion amplitudes. [6]
- 5.26 The study additionally demonstrates that modern large turbines increasingly utilise:
- “soft-stiff”;
- and in some cases:
- “soft-soft”;
- dynamic tower concepts. [6]
- 5.27 These approaches intentionally involve more flexible structural behaviour relative to earlier turbine generations.
- 5.28 This is highly relevant because modern turbine designs differ materially from the infrastructure assumptions underpinning the historic Eskdalemuir safeguarding framework.
- 5.29 Nagel et al. also confirm that:
- operational turbines generate significantly greater measurable ground vibration than non-operational turbines;
  - seismic measurements detect turbine-induced ground motion at distances extending several kilometres from source turbines. [6]
- 5.30 The broader literature therefore collectively demonstrates several important points relevant to Eskdalemuir:
- turbine-induced seismic propagation is well established scientifically;
  - lower-frequency propagation is particularly important;
  - cumulative multi-turbine interaction effects are complex;
  - attenuation behaviour varies substantially according to conditions;
  - seismic protection radii are already recognised internationally within seismological research.
- 5.31 Importantly however, the literature also consistently acknowledges uncertainty.
- 5.32 The reviewed studies repeatedly identify limitations associated with:
- far-field propagation modelling;
  - geological variability;
  - cumulative interaction effects;
  - generalising observations from individual sites;
  - predicting long-range attenuation behaviour under differing environmental conditions.

- 5.33 This limitation is particularly significant within the Eskdalemuir debate because some policy and industry discussions increasingly rely upon attenuation assumptions intended to support revised safeguarding approaches.
- 5.34 The literature itself demonstrates that propagation behaviour cannot always be simplified reliably into universal fixed-distance assumptions.
- 5.35 Instead, the scientific evidence indicates that turbine-induced seismic propagation is:
- highly condition dependent;
  - frequency dependent;
  - structurally dependent;
  - influenced by cumulative source interaction.
- 5.36 The wider scientific literature therefore supports a precautionary approach where:
- exceptionally sensitive monitoring infrastructure exists;
  - cumulative uncertainty remains significant;
  - turbine scale continues to increase materially beyond earlier infrastructure assumptions.

## References

- [1] Saccorotti, G., et al. (2011). Seismic noise by wind farms: A case study from the Virgo interferometer, Italy.
- [2] Friedrich, A., et al. (2018). Identification of wind farm seismic signals using migration analysis.
- [3] Westwood, R., & Styles, P. (2017). Polarization analysis of wind turbine induced seismic signals.
- [4] Gortsas, N., et al. (2017). Numerical simulation of wind turbine seismic wave propagation.
- [5] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.
- [6] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.

# SECTION 6

## MODERN TURBINE SCALE AND STRUCTURAL EVOLUTION



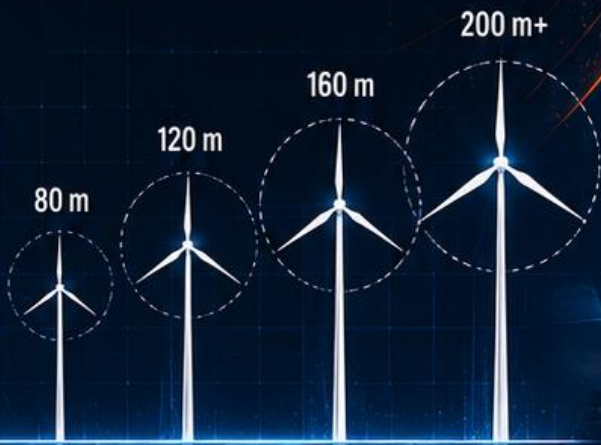
200 m+  
ROTOR DIAMETER



250 m+  
TIP HEIGHT



10-15 MW  
CAPACITY



## 6: Modern Turbine Scale and Structural Evolution

- 6.1 One of the most important issues within the modern Eskdalemuir safeguarding debate is the substantial change in turbine engineering and structural scale since the historic safeguarding framework originally emerged.
- 6.2 During the early 2000s, when the original safeguarding arrangements developed, typical onshore wind turbines within the United Kingdom commonly involved:
- generating capacities of approximately 1–2 MW;
  - hub heights commonly below approximately 80–100 m;
  - blade tip heights commonly below approximately 100–110 m;
  - materially smaller rotor swept areas;
  - smaller nacelle assemblies and tower systems.
- 6.3 By contrast, modern onshore turbines now commonly proposed across the United Kingdom frequently involve:
- generating capacities exceeding 6–7 MW;
  - hub heights exceeding 140–170 m;
  - blade tip heights exceeding 200–250 m;
  - substantially larger rotor diameters;
  - significantly heavier nacelle assemblies;
  - much larger reinforced concrete foundations.
- 6.4 The physical scale increase between these generations of turbine infrastructure is therefore substantial.
- 6.5 Importantly, the significance of this increase is not limited solely to turbine height.
- 6.6 Modern turbines additionally involve:
- greater rotating mass;
  - increased aerodynamic loading;
  - increased structural flexibility;
  - more complex resonance behaviour;
  - different tower dynamic characteristics.
- 6.7 The Nagel et al. study explains that turbine-induced seismic behaviour is heavily influenced by:
- structural stiffness;
  - natural frequencies;
  - tower bending behaviour;
  - resonance interaction;
  - operational loading conditions. [1]
- 6.8 The study further explains that as turbines increase in size, traditional “stiff-stiff” structural designs become increasingly impractical from both engineering and economic perspectives. [1]

- 6.9 Consequently, larger turbines increasingly utilise:
- “soft-stiff”;
- and in some cases:
- “soft-soft”;
- dynamic tower concepts. [1]
- 6.10 Under these approaches, the structural system intentionally permits greater flexibility and operates closer to excitation frequency conditions associated with rotor dynamics and natural structural frequencies.
- 6.11 Nagel et al. explain that resonance conditions must therefore be carefully managed because operational turbines may pass through resonance points during normal operation. [1]
- 6.12 These modern structural behaviours differ materially from earlier smaller turbine generations.
- 6.13 The significance of this distinction is that modern turbine-induced seismic behaviour cannot automatically be assumed equivalent to that associated with older infrastructure around which the historic Eskdalemuir safeguarding assumptions originally developed.
- 6.14 The Nagel study additionally examined a representative 2 MW turbine involving:
- a hub height of approximately 140 m;
  - a nacelle and rotor assembly mass of approximately 150 tonnes;
  - a hybrid tower structure mass of approximately 1,650 tonnes;
  - reinforced concrete foundations approximately 20 m in diameter. [1]
- 6.15 Even this representative turbine already substantially exceeds the dimensions of many earlier turbines existing when the historic Eskdalemuir framework originally emerged.
- 6.16 Modern commercial turbines now frequently exceed those characteristics considerably.
- 6.17 Contemporary large onshore turbines may involve:
- rotor diameters exceeding 150–170 m;
  - nacelle weights exceeding several hundred tonnes;
  - significantly larger concrete foundation systems;
  - greater cyclic loading transferred into supporting structures and foundations.
- 6.18 As turbine dimensions increase, several related effects also increase including:
- swept aerodynamic area;
  - blade loading;
  - bending moments;
  - structural deflection;
  - cyclic loading transfer into foundations.
- 6.19 These changes are highly relevant because the scientific literature demonstrates that turbine-induced seismic ground motion is strongly influenced by structural behaviour rather than simply turbine rotation alone.

- 6.20 Modern turbines therefore represent not merely “larger versions” of older turbines, but materially different dynamic systems.
- 6.21 The Limberger et al. study further demonstrates that multiple turbines generate interacting seismic wave fields whose propagation characteristics vary according to:
- frequency;
  - geometry;
  - phase interaction;
  - subsurface conditions. [2]
- 6.22 This is important because the cumulative seismic behaviour of large modern wind farms may become increasingly complex as:
- turbine numbers increase;
  - turbine dimensions increase;
  - rotor diameters increase;
  - operating frequencies interact across multiple installations.
- 6.23 The current Eskdalemuir policy debate therefore exists within an engineering context that differs materially from that which existed when the original safeguarding assumptions developed.
- 6.24 Importantly, this does not automatically establish that modern turbines are incompatible with Eskdalemuir safeguarding requirements.
- 6.25 However, it does demonstrate that:
- historic assumptions may no longer be fully representative;
  - continued reassessment remains justified;
  - cumulative uncertainty remains operationally relevant.
- 6.26 This issue becomes particularly important where policy discussions increasingly propose:
- revised Seismic Impact Limits;
  - revised attenuation assumptions;
  - expanded turbine deployment capacity within the wider safeguarding area.
- 6.27 Where turbine infrastructure has evolved materially beyond the original engineering assumptions underpinning historic safeguarding arrangements, it is scientifically prudent that:
- cumulative interaction effects;
  - propagation behaviour;
  - low-frequency persistence;
  - resonance characteristics;
- continue to be assessed cautiously.
- 6.28 This is especially important because the literature itself repeatedly acknowledges that turbine-induced seismic propagation remains:
- condition dependent;
  - geology dependent;
  - structurally dependent;
  - frequency dependent.

- 6.29 Consequently, increasing turbine scale strengthens the importance of precautionary reassessment rather than weakening it.
- 6.30 The central technical issue is therefore not whether modern turbines generate seismic effects entirely different in kind from earlier turbines. Rather, the issue is whether:
- substantially larger infrastructure;
  - materially altered structural dynamics;
  - increasing cumulative deployment pressures;

may progressively alter the assumptions underpinning a safeguarding framework originally developed around materially smaller turbine technology.

## References

- [1] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.
- [2] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.

# SECTION 7

FREQUENCY-DEPENDENT  
PROPAGATION,  
CUMULATIVE EFFECTS  
AND UNCERTAINTY



## 7: Frequency-Dependent Propagation, Cumulative Effects and Uncertainty

- 7.1 One of the most important findings emerging from the scientific literature is that turbine-induced seismic propagation cannot be described reliably using simplistic fixed-distance assumptions alone.
- 7.2 The reviewed studies consistently demonstrate that propagation behaviour depends upon a complex interaction between:
- signal frequency;
  - geological conditions;
  - turbine structural dynamics;
  - wave interference effects;
  - cumulative interaction between multiple turbines.
- 7.3 This issue is particularly important within the Eskdalemuir safeguarding debate because policy discussions increasingly reference attenuation assumptions intended to justify revised safeguarding methodologies and expanded development capacity.
- 7.4 The scientific literature demonstrates that attenuation behaviour varies substantially according to frequency.
- 7.5 Limberger et al. observed that lower-frequency seismic peaks propagated substantially further than higher-frequency signals. [1]
- 7.6 The study demonstrated that:
- higher-frequency seismic energy attenuated relatively rapidly;
  - lower-frequency energy persisted over materially greater distances;
  - measurable low-frequency peaks remained identifiable at the furthest observation locations within the study profile. [1]
- 7.7 These findings are highly significant because low-frequency seismic behaviour is particularly relevant within sensitive monitoring environments such as Eskdalemuir.
- 7.8 Lower-frequency seismic waves generally:
- attenuate more slowly;
  - propagate further through geological strata;
  - interact differently with subsurface conditions;
  - contribute more substantially to persistent background seismic elevation.
- 7.9 The literature additionally demonstrates that propagation behaviour varies materially according to geology.
- 7.10 Limberger et al. specifically modelled attenuation behaviour using variables including:
- seismic shear wave velocity;
  - subsurface quality factors;
  - geological layering;
  - surface wave propagation characteristics. [1]

7.11 Nagel et al. similarly note that:

- foundation conditions;
- damping behaviour;
- tower dynamics;
- local geology;

all materially influence the propagation and intensity of turbine-induced seismic ground motion. [2]

7.12 These findings are important because they demonstrate that attenuation observations derived from one site or geological setting cannot automatically be generalised universally across all conditions.

7.13 The scientific literature also demonstrates that cumulative multi-turbine interaction effects are highly important.

7.14 Limberger et al. observed that multiple turbines generated interacting seismic wave fields rather than isolated independent signals. [1]

7.15 The study found that phase relationships between turbines materially altered:

- radiation patterns;
- amplitude decay behaviour;
- cumulative propagation characteristics. [1]

7.16 Importantly, the authors concluded that phase differences between turbines could produce:

- constructive interference;
- destructive interference;
- varying propagation behaviour across different directions and distances.

7.17 This finding is highly relevant to modern large-scale wind farm development because contemporary wind farms frequently involve:

- multiple turbines operating simultaneously;
- large rotor diameters;
- extensive geographical layouts;
- cumulative dynamic interaction between numerous rotating structures.

7.18 Consequently, cumulative seismic behaviour may become increasingly complex as:

- turbine numbers increase;
- turbine dimensions increase;
- cumulative operational interaction increases.

7.19 The literature therefore does not support the assumption that turbine-induced seismic behaviour can always be simplified into:

- uniform attenuation distances;
- or:
- universally predictable propagation limits.

- 7.20 Instead, the scientific evidence demonstrates that propagation behaviour is:
- variable;
  - condition dependent;
  - frequency dependent;
  - dynamically interactive.
- 7.21 This uncertainty becomes particularly important where safeguarding policy concerns infrastructure specifically chosen because of exceptionally low surrounding seismic disturbance.
- 7.22 The literature also repeatedly acknowledges limitations regarding far-field interpretation and long-range propagation modelling.
- 7.23 Limberger et al. note that modelling propagation behaviour requires simplifying assumptions regarding:
- subsurface structure;
  - attenuation behaviour;
  - surface wave interaction;
  - seismic source characteristics. [1]
- 7.24 Nagel et al. similarly emphasise that turbine-induced vibration behaviour is influenced heavily by:
- structural dynamics;
  - resonance interaction;
  - operational loading conditions;
  - local environmental variables. [2]
- 7.25 Consequently, the scientific literature itself demonstrates that substantial uncertainty remains regarding:
- cumulative long-range propagation behaviour;
  - interaction between multiple large modern turbines;
  - long-term cumulative background seismic elevation within sensitive monitoring environments.
- 7.26 This uncertainty is highly relevant to the Eskdalemuir safeguarding issue because some policy discussions increasingly seek to support revised safeguarding approaches through shorter attenuation assumptions and revised modelling methodologies.
- 7.27 The literature does not establish that such approaches are necessarily incorrect.
- 7.28 However, the literature also does not support the conclusion that cumulative low-frequency safeguarding concerns become irrelevant beyond simplistic fixed distances in all geological and operational circumstances.
- 7.29 Instead, the reviewed studies consistently indicate that:
- propagation complexity remains significant;
  - cumulative interaction effects remain important;
  - geological variability materially affects outcomes;
  - low-frequency persistence remains operationally relevant.

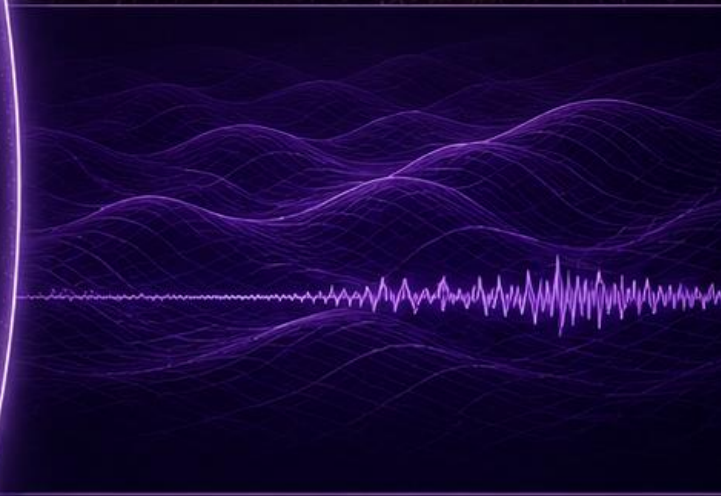
- 7.30 The scientific evidence therefore supports continued precaution where:
- exceptionally sensitive monitoring infrastructure exists;
  - cumulative industrialisation pressures continue increasing;
  - turbine scale continues evolving materially beyond earlier infrastructure assumptions;
  - uncertainty remains regarding long-term cumulative effects.
- 7.31 Importantly, the issue is not whether every turbine installation will automatically create unacceptable interference.
- 7.32 Rather, the issue concerns whether:
- cumulative background seismic elevation;
  - increasing turbine scale;
  - increasingly complex propagation behaviour;
  - progressive industrialisation surrounding sensitive monitoring infrastructure;
- may incrementally alter the exceptionally low-noise environmental conditions for which the Eskdalemuir site was originally selected.
- 7.33 This distinction is central to understanding why uncertainty itself strengthens the importance of precautionary safeguarding rather than weakening it.

## References

- [1] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.
- [2] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.

# SECTION 8

## THE PRECAUTIONARY IMPORTANCE OF LOW-NOISE SEISMIC ENVIRONMENTS



PROTECT SENSITIVE MONITORING



REDUCE BACKGROUND NOISE



IMPROVE DATA QUALITY & RELIABILITY



PRESERVE DETECTION CAPABILITY



SUPPORT GLOBAL SAFEGUARDING



RESPONSIBLE DEVELOPMENT



PROTECT FUTURE GENERATIONS

## 8: The Precautionary Importance of Low-Noise Seismic Environments

- 8.1 The central safeguarding issue surrounding Eskdalemuir is not solely the presence of turbine-induced seismic vibration itself. Rather, the issue concerns the long-term preservation of an exceptionally quiet seismic monitoring environment originally selected specifically because of its unusually low levels of anthropogenic disturbance.
- 8.2 The importance of low-noise seismic environments is well established within seismological monitoring practice.
- 8.3 Sensitive seismic monitoring systems are intentionally located within environments containing:
- minimal industrial activity;
  - low background vibration;
  - limited transport disturbance;
  - reduced anthropogenic seismic interference.
- 8.4 Nagel et al. explicitly confirm that seismic monitoring stations are intentionally positioned within environments containing minimal disruptive influences because of the sensitivity of seismic instrumentation. [1]
- 8.5 This principle is fundamental to understanding the Eskdalemuir safeguarding issue.
- 8.6 The monitoring capability of the Array depends not only upon the sensitivity of the instrumentation itself, but also upon maintaining surrounding environmental conditions sufficiently quiet to allow extremely faint seismic signals to be distinguished from persistent background disturbance.
- 8.7 The surrounding environment therefore forms part of the operational suitability of the site itself.
- 8.8 The original safeguarding philosophy reflected this principle.
- 8.9 Historically, the objective was primarily to preserve the naturally quiet seismic conditions surrounding the Array by limiting cumulative anthropogenic disturbance within the wider area.
- 8.10 This precautionary approach recognised that:
- low-frequency vibration can propagate over substantial distances;
  - cumulative effects may emerge gradually;
  - preserving quiet environmental conditions is operationally easier than attempting to reverse degradation after large-scale industrialisation occurs.
- 8.11 Importantly, the safeguarding concern is not that the monitoring system would suddenly cease functioning entirely following nearby development.
- 8.12 Instead, the concern relates to the possibility of incremental degradation through:
- progressive elevation of the background seismic noise floor;
  - increasing low-frequency interference;
  - reduced signal discrimination capability;
  - reduced sensitivity to weaker seismic events.

- 8.13 Such degradation may emerge gradually over long operational periods rather than through sudden operational failure.
- 8.14 This distinction is highly important because:
- stronger seismic events may remain detectable;
  - monitoring systems may continue functioning overall;
  - cumulative reduction in sensitivity may nevertheless occur progressively over time.
- 8.15 The reviewed scientific literature repeatedly demonstrates that turbine-induced seismic propagation involves:
- cumulative interaction effects;
  - frequency-dependent behaviour;
  - complex geological interaction;
  - uncertainty regarding long-range propagation characteristics. [1][2]
- 8.16 Consequently, the preservation of exceptionally quiet seismic environments becomes increasingly important where:
- scientific uncertainty remains;
  - cumulative industrialisation pressures increase;
  - turbine scale continues evolving;
  - monitoring infrastructure possesses strategic international significance.
- 8.17 Publicly available consultation and briefing material reviewed as part of this assessment indicates that some more recent policy discussions increasingly focus upon:
- upgraded monitoring technologies;
  - revised attenuation assumptions;
  - borehole sensor systems;
  - revised modelling methodologies intended to accommodate increased surrounding development capacity.
- 8.18 This represents an important conceptual shift within the safeguarding debate.
- 8.19 Historically, the safeguarding philosophy focused primarily upon preserving the quiet environmental conditions surrounding the Array itself.
- 8.20 Some more recent proposals increasingly focus upon adapting the monitoring system and mitigation methodologies so that greater surrounding anthropogenic disturbance may potentially be accommodated.
- 8.21 This distinction is strategically significant.
- 8.22 One approach prioritises maintaining the environmental characteristics for which the Eskdalemuir site was originally selected.
- 8.23 The alternative approach increasingly focuses upon technological adaptation intended to preserve monitoring capability despite increasing surrounding disturbance.

8.24 The existence of such proposals is not improper. It is entirely legitimate for:

- Governments;
- developers;
- consultants;
- infrastructure operators;

to explore technological mitigation and revised monitoring methodologies.

8.25 However, the emergence of such proposals demonstrates that:

- cumulative disturbance remains operationally relevant;
- increasing development pressures continue to challenge historic safeguarding assumptions;
- the issue remains technically unresolved.

8.26 This becomes particularly important because exceptionally quiet seismic environments are inherently difficult to recreate once materially altered through cumulative infrastructure development.

8.27 Once:

- large-scale industrial infrastructure;
- cumulative turbine arrays;
- associated transport networks;
- supporting grid infrastructure;

become established across a monitoring environment, restoring the original low-noise characteristics may prove practically impossible.

8.28 The precautionary issue is therefore not merely whether mitigation systems can maintain acceptable operational performance today.

8.29 The broader issue concerns whether:

- long-term cumulative disturbance;
- increasing industrialisation;
- evolving turbine scale;
- progressively revised safeguarding assumptions;

may gradually alter the very environmental conditions which originally made the Eskdalemuir site suitable for highly sensitive seismic monitoring.

8.30 This issue is particularly important because the Eskdalemuir Array forms part of internationally significant treaty-monitoring infrastructure associated with nuclear test detection obligations.

8.31 In such circumstances, precaution does not require proof of imminent catastrophic failure before safeguarding concerns become legitimate.

8.32 Instead, precaution becomes relevant precisely because:

- cumulative effects may emerge gradually;
- uncertainty remains significant;
- consequences may be strategically important;
- environmental degradation may become difficult or impossible to reverse once established.

8.33 The scientific literature reviewed within this report therefore supports continued precautionary safeguarding where:

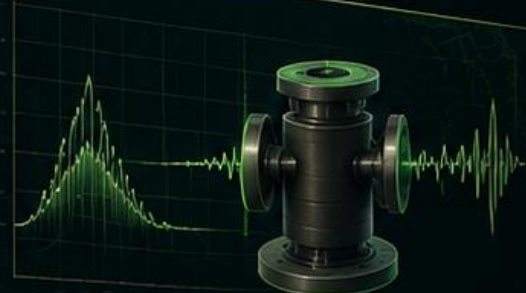
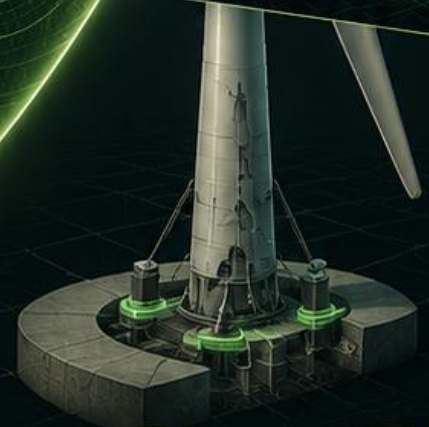
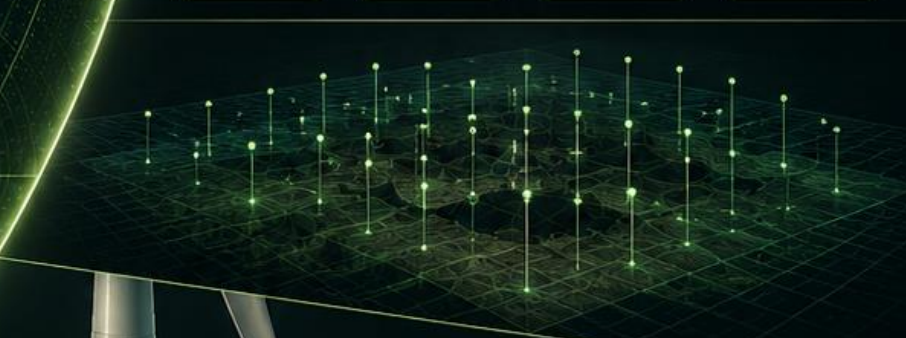
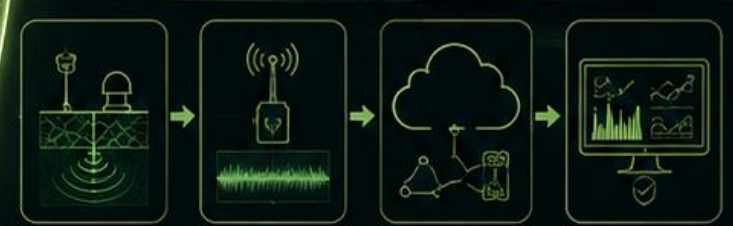
- exceptionally sensitive seismic monitoring infrastructure exists;
- cumulative industrialisation pressures continue increasing;
- uncertainty remains regarding long-term propagation and cumulative effects;
- modern turbine infrastructure differs materially from the assumptions underpinning earlier safeguarding frameworks.

## References

- [1] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.
- [2] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.

# SECTION 9

## REVIEW OF EMERGING MITIGATION AND MONITORING UPGRADE PROPOSALS



## 9: Review of Emerging Mitigation and Monitoring Upgrade Proposals

- 9.1 The current Eskdalemuir policy debate increasingly involves proposals intended to permit greater levels of wind turbine development within the wider safeguarding area through revised technical methodologies and upgraded monitoring systems.
- 9.2 Publicly available consultation and briefing material reviewed as part of this assessment references several proposed approaches including:
- upgraded borehole seismic monitoring systems;
  - revised attenuation modelling methodologies;
  - revised Seismic Impact Limit calculations;
  - revised cumulative assessment approaches;
  - technical mitigation intended to maintain operational monitoring capability despite increasing surrounding development.
- 9.3 The existence of such proposals is not unusual within major infrastructure policy discussions.
- 9.4 It is entirely normal for:
- developers;
  - technical consultants;
  - industry bodies;
  - Governments;
- to explore revised methodologies and technological mitigation measures where significant infrastructure and economic interests are involved.
- 9.5 Similarly, the commissioning of technical research by developers or industry groups does not, in itself, invalidate the underlying work produced.
- 9.6 However, the existence of competing methodologies and evolving mitigation proposals demonstrates that:
- the safeguarding issue remains technically active;
  - cumulative turbine-induced seismic disturbance remains operationally relevant;
  - substantial policy disagreement continues regarding how precaution should be applied.
- 9.7 One of the central themes emerging within the current debate is the increasing use of attenuation modelling intended to demonstrate that turbine-induced seismic effects reduce substantially over shorter distances than previously assumed.
- 9.8 Some technical proposals additionally suggest that upgraded borehole sensor systems may reduce sensitivity to near-surface anthropogenic seismic disturbance.
- 9.9 In principle, such proposals may offer operational advantages under certain environmental conditions.

- 9.10 Borehole seismic systems are widely recognised within seismological practice as potentially reducing exposure to:
- surface environmental noise;
  - weather-related disturbance;
  - shallow anthropogenic vibration sources.
- 9.11 However, the existence of potential mitigation options does not eliminate the underlying safeguarding issue.
- 9.12 Rather, these proposals effectively represent a different safeguarding philosophy from that which originally underpinned the historic Eskdalemuir framework.
- 9.13 Historically, the safeguarding objective focused primarily upon preserving the naturally quiet seismic environment surrounding the Array itself.
- 9.14 Some more recent proposals instead increasingly focus upon adapting the monitoring system and technical methodologies in order to accommodate increasing surrounding anthropogenic disturbance.
- 9.15 This distinction is strategically important.
- 9.16 One approach prioritises environmental preservation around the monitoring installation.
- 9.17 The alternative approach increasingly focuses upon maintaining operational capability despite increasing surrounding industrialisation through:
- upgraded monitoring systems;
  - revised modelling approaches;
  - revised attenuation assumptions;
  - technical mitigation measures.
- 9.18 Importantly, the reviewed scientific literature itself repeatedly acknowledges uncertainty regarding:
- cumulative long-range propagation;
  - geological variability;
  - multi-turbine interaction behaviour;
  - frequency-dependent attenuation;
  - far-field modelling assumptions. [1][2]
- 9.19 Consequently, while revised methodologies and mitigation systems may potentially improve monitoring resilience under certain conditions, the scientific literature does not establish that cumulative safeguarding concerns become irrelevant.
- 9.20 The literature instead demonstrates that:
- propagation behaviour remains complex;
  - attenuation varies materially according to conditions;
  - lower-frequency persistence remains significant;
  - cumulative interaction effects remain difficult to generalise universally.

- 9.21 This is particularly important because modern wind farms increasingly involve:
- larger turbines;
  - greater turbine densities;
  - larger rotor diameters;
  - greater cumulative rotating mass;
  - increasingly complex dynamic interaction.
- 9.22 The current policy debate therefore concerns more than whether mitigation technologies can function technically under certain operational conditions.
- 9.23 The broader issue concerns whether:
- progressively revised safeguarding assumptions;
  - increasing cumulative industrialisation;
  - expanding turbine deployment pressure;
- may gradually alter the environmental conditions originally considered necessary for highly sensitive seismic monitoring.
- 9.24 Publicly available material reviewed as part of this assessment additionally indicates increasing discussion surrounding:
- allocation of remaining Seismic Impact Limit capacity;
  - prioritisation of development opportunities;
  - revised cumulative capacity management within the wider safeguarding area.
- 9.25 This reflects increasing pressure upon the historic safeguarding framework as modern turbine deployment continues expanding.
- 9.26 The reviewed material also indicates that some parties advocate greater reliance upon:
- developer-funded modelling tools;
  - revised predictive methodologies;
  - operational mitigation systems.
- 9.27 Such approaches may provide useful technical information and modelling capability.
- 9.28 However, where:
- cumulative uncertainty remains significant;
  - turbine infrastructure continues evolving rapidly;
  - strategic monitoring infrastructure is involved;
- precautionary scrutiny remains justified regarding:
- modelling assumptions;
  - validation methodologies;
  - long-term cumulative interaction effects;
  - operational resilience over extended periods.
- 9.29 This is particularly relevant because the reviewed scientific literature repeatedly demonstrates that turbine-induced seismic propagation cannot presently be simplified reliably into universally applicable fixed-distance assumptions.

9.30 The central issue is therefore not whether mitigation technologies and revised methodologies possess technical merit.

9.31 Rather, the issue concerns whether:

- evolving safeguarding methodologies;
- increasing tolerance for surrounding disturbance;
- expanding cumulative development pressure;

remain fully compatible with preserving the exceptionally quiet seismic conditions for which the Eskdalemuir site was originally selected.

9.32 The continuing existence of Government consultation, competing technical interpretations and evolving mitigation proposals itself demonstrates that these questions remain unresolved and strategically important.

## References

- [1] Limberger, F., Lindenfeld, M., Deckert, H., & Rümpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.
- [2] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.

# SECTION 10

## STRATEGIC POLICY AND SAFEGUARDING CONSIDERATIONS



## 10: Strategic Policy and Safeguarding Considerations

- 10.1 The Eskdalemuir safeguarding issue extends beyond a narrow technical disagreement concerning turbine vibration measurements alone.
- 10.2 The debate increasingly raises broader strategic questions concerning:
- infrastructure safeguarding;
  - cumulative industrialisation;
  - long-term environmental preservation;
  - uncertainty management;
  - proportional precaution around internationally significant monitoring infrastructure.
- 10.3 The Eskdalemuir Array forms part of a wider international monitoring network associated with nuclear test detection and treaty verification obligations.
- 10.4 Consequently, the safeguarding issue differs materially from ordinary planning disputes involving:
- visual amenity;
  - landscape impact;
  - localised environmental effects.
- 10.5 The relevant policy issue instead concerns the long-term preservation of a monitoring environment originally selected because of its unusually low levels of anthropogenic seismic disturbance.
- 10.6 Importantly, the current debate does not concern whether renewable energy development should occur generally within the United Kingdom.
- 10.7 Nor does the issue concern whether wind turbines are capable of generating electricity successfully.
- 10.8 The central issue instead concerns whether progressively increasing industrialisation surrounding strategically important seismic monitoring infrastructure remains compatible with preserving the exceptionally low-noise conditions for which the Eskdalemuir site was originally selected.
- 10.9 This distinction is important because the current policy discussion increasingly occurs within a broader context involving:
- accelerated renewable energy deployment;
  - major grid infrastructure expansion;
  - increasing electricity demand;
  - wider energy security policy objectives.
- 10.10 Publicly available briefing material reviewed as part of this assessment indicates increasing pressure to maximise development opportunities within areas previously constrained by Eskdalemuir safeguarding arrangements.

- 10.11 Some of the reviewed material additionally frames revised safeguarding methodologies as necessary to facilitate:
- increased renewable generation capacity;
  - associated infrastructure investment;
  - wider economic development objectives.
- 10.12 Such policy objectives are entirely legitimate matters for Government consideration.
- 10.13 However, the existence of broader infrastructure and economic policy objectives does not eliminate the need for careful precaution where strategically important monitoring infrastructure is involved.
- 10.14 This is particularly relevant because the scientific literature reviewed within this report repeatedly demonstrates that:
- cumulative interaction effects remain complex;
  - propagation behaviour remains condition dependent;
  - uncertainty remains significant regarding long-range cumulative behaviour. [1][2]
- 10.15 The literature additionally demonstrates that modern turbine infrastructure differs materially from the assumptions underpinning earlier safeguarding arrangements.
- 10.16 Consequently, the burden of justification surrounding significant relaxation of historic safeguarding principles should remain substantial.
- 10.17 The issue is especially important because:
- large-scale turbine infrastructure is long-term in nature;
  - associated industrialisation may become effectively irreversible once established;
  - restoring exceptionally quiet seismic conditions may prove impractical following cumulative infrastructure development.
- 10.18 This creates an important asymmetry within the policy debate.
- 10.19 If precautionary safeguards are maintained while further research and monitoring continue, development opportunities may potentially remain constrained within parts of the wider safeguarding area.
- 10.20 However, if large-scale cumulative industrialisation proceeds and long-term safeguarding assumptions later prove insufficient, restoring the original environmental conditions surrounding the Array may become extremely difficult or impossible in practical terms.
- 10.21 This distinction is fundamental to precautionary infrastructure safeguarding.
- 10.22 Precaution does not require proof of imminent catastrophic operational failure before concerns become legitimate.
- 10.23 Rather, precaution becomes especially important where:
- uncertainty remains unresolved;
  - impacts may emerge cumulatively over long periods;
  - environmental degradation may be difficult to reverse;
  - strategically significant infrastructure is involved.

- 10.24 The current Eskdalemuir debate increasingly appears to involve two competing safeguarding philosophies.
- 10.25 The first approach prioritises preserving the naturally quiet seismic environment surrounding the Array itself.
- 10.26 The second approach increasingly focuses upon:
- revised attenuation assumptions;
  - upgraded monitoring systems;
  - revised modelling methodologies;
  - operational mitigation measures;
- intended to maintain monitoring capability despite increasing surrounding anthropogenic disturbance.
- 10.27 Both approaches may possess technical and policy rationale.
- 10.28 However, they represent materially different approaches to risk management.
- 10.29 One approach prioritises preventing degradation of the surrounding seismic environment.
- 10.30 The alternative approach increasingly focuses upon technological adaptation intended to tolerate increasing surrounding disturbance while maintaining acceptable operational performance.
- 10.31 The scientific literature reviewed within this report does not conclusively establish that either approach is definitively correct in all circumstances.
- 10.32 However, the literature does consistently demonstrate that:
- turbine-induced seismic propagation is real;
  - propagation behaviour remains complex;
  - cumulative uncertainty remains significant;
  - modern turbine dynamics differ materially from earlier infrastructure assumptions.
- 10.33 Consequently, the existence of continuing scientific uncertainty strengthens rather than weakens the rationale for proportionate precaution.
- 10.34 This is particularly relevant where:
- internationally significant treaty-monitoring infrastructure exists;
  - cumulative industrialisation pressures continue increasing;
  - turbine infrastructure continues evolving rapidly in scale and complexity.
- 10.35 Ultimately, the strategic safeguarding issue surrounding Eskdalemuir is not simply whether current monitoring systems can technically continue operating under revised conditions.

10.36 The broader issue concerns whether:

- progressively revised safeguarding assumptions;
- increasing tolerance for surrounding industrialisation;
- cumulative long-term environmental alteration;

remain fully compatible with preserving the exceptional low-noise seismic conditions for which the site was originally selected.

10.37 The continuing existence of Government consultation, evolving mitigation proposals and competing technical interpretations itself demonstrates that these questions remain strategically significant and unresolved.

## References

- [1] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.
- [2] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.

# SECTION 11

## INDICATIVE SCALING ASSESSMENT AND SAFEGUARDING IMPLICATIONS



DEPLOYMENT SCALING



SEISMIC IMPACT SCALING



CUMULATIVE EXPOSURE



PROTECT SENSITIVE ENVIRONMENTS

SETBACK STRATEGIES

MONITORING THRESHOLDS

COMMUNITY ENGAGEMENT



# 11: Indicative Scaling Assessment and Safeguarding Implications

- 11.1 The following section provides an indicative comparative scaling assessment examining how modern turbine dimensions differ from the infrastructure assumptions that existed when the historic Eskdalemuir safeguarding framework originally developed.
- 11.2 This section does not present:
- formal Ministry of Defence modelling;
  - official safeguarding boundaries;
  - definitive propagation calculations;
  - validated CTBT operational analysis.
- 11.3 Instead, the purpose of this section is to illustrate why:
- continued reassessment remains justified;
  - modern turbine infrastructure may not be directly comparable to earlier turbine generations;
  - precautionary safeguarding concerns remain operationally relevant.
- 11.4 The historic Eskdalemuir safeguarding framework largely emerged during a period when typical UK onshore turbines commonly involved:
- generating capacities of approximately 1–2 MW;
  - blade tip heights commonly below approximately 100–110 m;
  - materially smaller rotor diameters and structural systems.
- 11.5 Modern onshore turbines now commonly proposed within the United Kingdom frequently involve:
- generating capacities exceeding 6–7 MW;
  - blade tip heights exceeding 200–250 m;
  - substantially larger rotor swept areas;
  - heavier nacelles and rotating assemblies;
  - significantly larger foundations and tower systems.
- 11.6 The scientific literature reviewed within this report demonstrates that turbine-induced seismic behaviour is strongly influenced by:
- structural dynamics;
  - tower flexibility;
  - resonance interaction;
  - modal frequencies;
  - cumulative wave interaction. [1][2]
- 11.7 Consequently, simple geometric comparison alone does not fully capture the engineering significance of modern turbine scale increases.
- 11.8 However, an indicative comparative scaling exercise may still assist in illustrating the extent to which modern infrastructure differs from the assumptions underpinning the historic safeguarding framework.
- 11.9 Publicly available consultation material references revised Seismic Impact Limit methodologies associated with installed turbine generating capacity.

11.10 One indicative relationship discussed within the consultation involves broad scaling linked to the square root of installed generating capacity.

11.11 Using that indicative comparative relationship:

A representative historic turbine:

2 MW

A representative modern turbine:

7 MW

11.12 Applying square-root scaling:

$$\sqrt{2} = 1.414$$

$$\sqrt{7} = 2.646$$

11.13 Producing an indicative relative scaling factor of:

$$2.646 \div 1.414 = \text{approximately } 1.87$$

11.14 Applying this purely as an illustrative comparative exercise against the historic 50 km safeguarding radius would produce:

$$50 \text{ km} \times 1.87 = \text{approximately } 93.5 \text{ km}$$

11.15 **It is critically important that this figure is interpreted cautiously and responsibly.**

11.16 The scientific literature expressly demonstrates that propagation behaviour depends heavily upon:

- geology;
- frequency characteristics;
- cumulative interaction effects;
- structural dynamics;
- attenuation behaviour;
- operational conditions. [1][2]

11.17 Consequently, the approximately 94 km figure should not be interpreted as:

- formal safeguarding recommendation;
- a scientifically validated exclusion radius;
- an official MOD assessment;
- evidence that all development within such distances would necessarily create unacceptable effects.

11.18 Rather, the calculation demonstrates an important precautionary principle:

Modern turbine infrastructure differs materially from the turbine infrastructure around which the historic Eskdalemuir safeguarding assumptions originally developed.

11.19 The scientific literature additionally demonstrates that:

- lower-frequency signals propagate substantially further than higher-frequency signals;
- cumulative multi-turbine interaction effects are complex;
- attenuation behaviour varies significantly according to geological conditions. [1]

11.20 Limberger et al. specifically observed that:

- lower-frequency peaks remained identifiable at the furthest observation locations within their measurement profile;
- phase interaction between turbines materially altered radiation patterns and amplitude decay behaviour. [1]

11.21 These findings are highly relevant because modern wind farms increasingly involve:

- larger turbines;
- greater turbine densities;
- larger rotor diameters;
- more complex cumulative interaction effects.

11.22 Consequently, the current safeguarding debate cannot reasonably be reduced to simplistic assumptions that:

- impacts disappear uniformly after a fixed distance;  
or:
- modern turbine infrastructure behaves identically to earlier turbine generations.

11.23 In light of both the scientific literature and the acknowledged uncertainties within that literature, a more cautious interpretation would recognise several indicative safeguarding sensitivity zones.

11.24 On an illustrative precautionary basis, the following conceptual framework may reasonably be considered:

**Core exclusion and highest sensitivity zone:**

0 to 15 km | 0 to 9.32 miles

**Historic safeguarding and cumulative assessment zone:**

15 to 50 km | 9.32 to 31.07 miles

**Enhanced modern turbine precautionary review zone:**

50 to 75 km | 31.07 to 46.60 miles

**Outer cumulative interaction and technical review zone:**

75 to 94 km | 46.6 to 58.41 miles

11.25 These indicative zones are not presented as formal policy recommendations.

11.26 Rather, they are intended to demonstrate that:

- modern turbine infrastructure materially exceeds historic infrastructure assumptions;
- cumulative interaction complexity remains significant;
- continued precautionary reassessment remains justified.

11.27 Importantly, the proposed “enhanced review” and “technical review” concepts do not imply that all development beyond 50 km should automatically be prohibited.

11.28 Instead, they reflect the precautionary observation that:

- cumulative low-frequency propagation remains complex;
- attenuation behaviour remains variable;
- long-term interaction effects remain uncertain;
- modern turbine infrastructure differs materially from historic assumptions.

11.29 The reviewed scientific literature therefore supports a cautious interpretation whereby:

- increasing turbine scale strengthens the importance of reassessment; rather than:
- automatically justifying relaxation of precautionary safeguarding assumptions.

11.30 Ultimately, the central issue is not whether a precise revised safeguarding radius can presently be proven mathematically.

11.31 The more important issue is whether:

- progressively larger turbine infrastructure;
- increasing cumulative industrialisation;
- evolving safeguarding methodologies;

may gradually alter the exceptionally quiet seismic conditions originally considered necessary for highly sensitive international monitoring infrastructure.

11.32 The scientific literature reviewed within this report demonstrates that this question remains technically relevant, operationally significant and not conclusively resolved.

## References

- [1] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.
- [2] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.

# SECTION 12

## CONCLUSIONS



UNDERSTAND



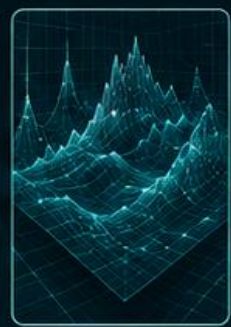
PROTECT



IMPROVE



COLLABORATE



## 12: Conclusions

- 12.1 The scientific and policy debate surrounding the Eskdalemuir Seismic Array is not a dispute over whether turbine-induced seismic ground motion exists.
- 12.2 The existence of measurable turbine-induced seismic propagation is already established within:
- peer-reviewed engineering literature;
  - seismological research;
  - the historic safeguarding framework itself. [1][2]
- 12.3 The central issue instead concerns:
- cumulative long-term effects;
  - acceptable levels of background seismic disturbance;
  - whether historic safeguarding assumptions remain representative of modern turbine infrastructure;
  - how precaution should be applied around internationally significant monitoring infrastructure.
- 12.4 The reviewed literature consistently demonstrates that:
- operating wind turbines generate measurable seismic ground motion;
  - lower-frequency propagation is particularly significant;
  - attenuation behaviour varies according to frequency and geology;
  - cumulative interaction effects between turbines are complex;
  - propagation behaviour cannot reliably be reduced to simplistic universal fixed-distance assumptions. [1][2]
- 12.5 The literature additionally demonstrates that turbine-induced seismic behaviour is strongly influenced by:
- structural dynamics;
  - resonance behaviour;
  - tower flexibility;
  - modal frequencies;
  - cumulative wave interaction. [1]
- 12.6 These findings are especially important because modern turbine infrastructure differs materially from the infrastructure assumptions underpinning the historic Eskdalemuir safeguarding framework.
- 12.7 Contemporary turbines now frequently involve:
- substantially larger rotor diameters;
  - significantly greater structural mass;
  - taller and more flexible tower systems;
  - more complex dynamic behaviour;
  - materially greater cumulative loading effects.
- 12.8 Consequently, modern turbine infrastructure cannot automatically be assumed fully comparable to the smaller turbine generations around which the original safeguarding arrangements emerged during the early 2000s.

- 12.9 The reviewed scientific literature also repeatedly acknowledges significant uncertainty regarding:
- long-range propagation behaviour;
  - cumulative interaction effects;
  - geological variability;
  - far-field attenuation modelling;
  - long-term cumulative background seismic elevation. [1][2]
- 12.10 This uncertainty is particularly important because the Eskdalemuir Array was intentionally located within an unusually quiet seismic environment specifically to support highly sensitive seismic monitoring capability.
- 12.11 The surrounding low-noise environmental conditions therefore form part of the operational suitability of the site itself.
- 12.12 Historically, the safeguarding philosophy focused primarily upon preserving those quiet environmental conditions through precautionary limitation of cumulative surrounding disturbance.
- 12.13 Some more recent policy discussions increasingly focus instead upon:
- revised attenuation methodologies;
  - upgraded borehole monitoring systems;
  - revised Seismic Impact Limits;
  - mitigation systems intended to accommodate increased surrounding development.
- 12.14 This represents an important conceptual evolution within the safeguarding debate.
- 12.15 One approach prioritises preserving the naturally quiet seismic environment surrounding the Array.
- 12.16 The alternative approach increasingly focuses upon adapting monitoring systems and technical methodologies in order to maintain operational capability despite increasing surrounding anthropogenic disturbance.
- 12.17 The reviewed literature does not conclusively establish that either approach is definitively correct in all circumstances.
- 12.18 However, the literature consistently demonstrates that:
- propagation complexity remains significant;
  - cumulative interaction effects remain operationally relevant;
  - uncertainty remains substantial;
  - modern turbine infrastructure materially differs from historic assumptions.
- 12.19 Consequently, the existence of uncertainty strengthens rather than weakens the importance of proportionate precautionary safeguarding.
- 12.20 This is particularly relevant where:
- internationally significant treaty-monitoring infrastructure exists;
  - cumulative industrialisation pressures continue increasing;
  - environmental degradation may become difficult or impossible to reverse once established.

12.21 The indicative comparative scaling assessment presented within this report is not intended to establish definitive revised safeguarding boundaries.

12.22 Rather, the scaling exercise illustrates an important precautionary observation:

Modern turbine infrastructure materially exceeds the scale and structural assumptions underpinning the historic safeguarding framework.

12.23 The reviewed scientific literature therefore supports continued reassessment and caution regarding:

- cumulative low-frequency disturbance;
- modern turbine interaction effects;
- long-term environmental preservation surrounding the Array.

12.24 Ultimately, the central safeguarding issue is not whether modern monitoring systems can technically continue operating under revised conditions.

12.25 The broader issue concerns whether:

- progressively increasing surrounding industrialisation;
- evolving safeguarding methodologies;
- increasing tolerance for anthropogenic seismic disturbance;

remain fully compatible with preserving the exceptionally quiet seismic environment for which the Eskdalemuir site was originally selected.

12.26 The continuing existence of Government consultation, evolving mitigation proposals and competing technical interpretations itself demonstrates that these questions remain unresolved, strategically significant and operationally relevant.

12.27 In such circumstances, a precautionary safeguarding approach remains justified until:

- cumulative long-term effects are better understood;
- modern turbine interaction behaviour is more fully characterised;
- sufficient evidence exists to demonstrate that increasing surrounding industrialisation will not materially degrade the low-noise seismic conditions upon which the operational suitability of the Eskdalemuir Array originally depended.

## References

- [1] Limberger, F., Lindenfeld, M., Deckert, H., & Rumpker, G. (2021). Seismic radiation from wind turbines: observations and analytical modeling of frequency-dependent amplitude decays. *Solid Earth*, 12, 1851–1864.
- [2] Nagel, S., Zieger, T., Luhmann, B., Knödel, P., Ritter, J., & Ummenhofer, T. (2021). Ground motions induced by wind turbines. *Civil Engineering Design*, 3, 73–86.



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