Technical Appendix

Drummarnock Wind Farm

Technical Appendix 8-2: Peat Landslide Hazard and Risk Assessment

Drummarnock Wind Farm Limited

July 2024

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Glossary of Terms

Term	Definition
The Applicant	Drummarnock Wind Farm Ltd
The Agent	Atmos Consulting Limited
Environmental Advisors and Planning Consultants	Atmos Consulting Limited
Environmental Impact Assessment	Environmental Impact Assessment (EIA) is a means of carrying out, in a systematic way, an assessment of the likely significant environmental effects from a development.
Environmental Impact Assessment Regulations	Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017
Environmental Impact Assessment Report	A document reporting the findings of the EIA and produced in accordance with the EIA Regulations
The Proposed Development	Drummarnock Wind Farm
The Proposed Development Site	The land enclosed by the red line shown on Figure 1-1

List of Abbreviations

Abbreviation	Description
AOD	Above Ordnance Datum
BGS	British Geological Society
BPG	Best Practice Guidance
DWPA	Drinking Water Protected Area
EIA	Environmental Impact Assessment
EIAR	Environmental Impact Assessment Report
ECU	Energy Consents Unit
FoS	Factor of Safety
GIS	Geographical Information Science
Ha	hectare
LIDAR	Light Detection And Ranging
NGR	National Grid Reference
NVC	National Vegetation Classification
OPMP	Outline Peat Management Plan
PLHRA	Peat Landslide Hazard and Risk Assessment
SEPA	Scottish Environmental Protection Agency

1 Introduction

1.1 Background

Drummarnock Wind Farm Limited ('the Applicant') is intending to apply for Consent under the Town and Country Planning (Scotland) Act 1997 (as amended) ('the Planning Act') to develop a wind farm consisting of 4 wind turbines of up to 180m in height and associated infrastructure (the 'Proposed Development').

The Proposed Development would be located at National Grid Reference (NGR) NS 75471 87114, circa 10km south-west of Stirling, in the Fintry, Gargunnock and Touch Hills, within the planning authority area of Stirling Council. A detailed description of the Proposed Development is provided in Chapter 3 Description of Development.

The Scottish Government Best Practice Guidance (BPG) provides a screening tool to determine whether a peat landslide hazard and risk assessment (PLHRA) is required (Scottish Government, 2017).

This is in the form of a flowchart, which specifies that where blanket peat is present, slopes exceed 2° and proposed infrastructure is located on peat, a PLHRA should be prepared.

While this guidance applies only to applications under Section 36 of the Electricity Act 1989; it is considered good practice to undertake stability assessments wherever peat may be present in the vicinity of proposed infrastructure. As these conditions exist at the Proposed Development Site, a PLHRA has been undertaken.

1.2 Scope of Work

The scope of the PLHRA is as follows:

- Characterise the peatland geomorphology of Proposed Development Site to determine whether prior incidences of instability have occurred and whether contributory factors that might lead to instability in the future are present across Proposed Development Site;
- Determine the likelihood of a future peat landslide under natural conditions and in association with construction activities associated with the Proposed Development;
- Identify potential receptors that might be affected by peat landslides, should they occur, and quantify the associated risks; and
- Provide appropriate mitigation and control measures to reduce risks to acceptable levels such that the Proposed Development is developed safely and with minimal risks to the environment.

The contents of this PLHRA have been prepared in accordance with the BPG, noting that the guidance "*should not be taken as prescriptive or used as a substitute for the developer's [consultant's] preferred methodology*" (Scottish Government, 2017). The first edition of the Scottish Government Best Practice Guidance (BPG) was issued in 2007 and provided an outline of expectations for approaches to be taken in assessing peat landslide risks on wind farm sites. After ten years of practice and industry experience, the BPG was reissued in 2017, though without fundamental changes to the core expectations. A key change was to provide clearer steer on the format and outcome of reviews undertaken by the Energy Consents Unit (ECU) checking authority and related expectations of report revisions, should they be required.

In section 4.1 of the BPG, the key elements of a PLHRA are highlighted, as follows (Scottish Government, 2017):

- An assessment of the character of the peatland within the application boundary including thickness and extent of peat, and a demonstrable understanding of site hydrology and geomorphology;
- An assessment of evidence for past landslide activity and present-day instability e.g. pre-failure indicators;
- A qualitative or quantitative assessment of the potential for or likelihood of future peat landslide activity (or a landslide susceptibility or hazard assessment);
- Identification of receptors (e.g. habitats, watercourses, infrastructure, human life) exposed to peat landslide hazards; and
- A site-wide qualitative or quantitative risk assessment that considers the potential consequences of peat landslides for the identified receptors.

Section 1.3 describes how this report addresses this indicative scope.

1.3 Report Structure

This report is structured as follows:

- Section 2 gives context to the landslide risk assessment methodology through a literature based account of peat landslide types and contributory factors, including review of any published or anecdotal information available concerning previous instability at or adjacent to Proposed Development Site;
- Section 3 provides a site description based on desk study and site observations, including consideration of aerial or satellite imagery, digital elevation data, geology and peat depth data;
- Section 4 describes the approach to and results of an assessment of peat landslide likelihood under both natural conditions and in association with construction of the Proposed Development; and
- Section 5 provides mitigation and control measures to reduce or minimise these risks prior to, during and after construction.

Assessments within the PLHRA have been undertaken alongside assessments for the Peat Management Plan (Technical Appendix 8-3) and have been informed by results from the peat depth survey.

Where relevant information is available elsewhere in the Environmental Impact Assessment Report (EIAR), this is referenced in the text rather than repeated in this report.

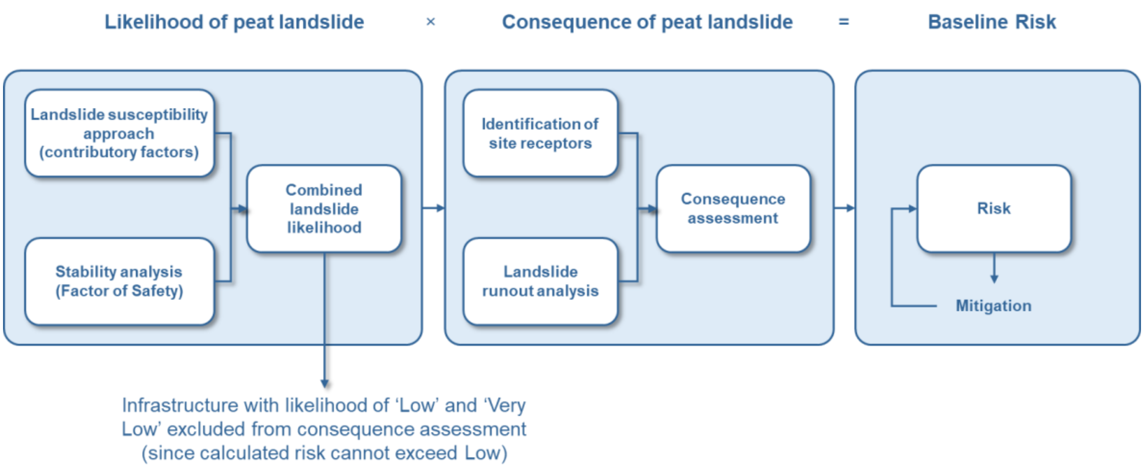
1.4 Approaches to Assessing Peat Instability for the Proposed Development

This report approaches assessment of peat instability through both a qualitative contributory factor-based approach and via more conventional stability analysis (through limit equilibrium or Factor of Safety (FoS) analysis). The advantage of the former is that many observed relationships between reported peat landslides and ground conditions can be considered together where a FoS is limited to consideration of a limited number of geotechnical parameters. The disadvantage is that the outputs of such an approach are better at illustrating relative variability in landslide susceptibility across a site rather than absolute likelihood.

The advantage of the FoS approach is that clear thresholds between stability and instability can be defined and modelled numerically, however, in reality, there is considerable uncertainty in input parameters and it is a generally held view that the geomechanical basis for stability analysis in peat is limited given the nature of peat as an organic, rather than mineral soil.

To reflect these limitations, both approaches are adopted and outputs from each approach integrated in the assessment of landslide likelihood. Plate 8-2-1 shows the approach:

Plate 8-2-1: Risk Assessment Approach



1.5 Team Competencies

This PLHRA has been undertaken by a chartered geologist with 25+ years' experience of mapping and interpreting peatland terrains and peat instability features. Geomorphological walkover survey was undertaken by the same individual. Peat depth probing was undertaken by Atmos Consulting, an experienced peatland survey team, and additional site observations were made available from these surveys to the PLHRA team.

2 Background To Peat Instability

2.1 Peat Instability in the UK and Ireland

This section reviews published literature to highlight commonly identified landscape features associated with recorded peat landslides in the UK and Ireland. This review forms the basis for identifying similar features at the Proposed Development and using them to understand the susceptibility of Proposed Development Site to naturally occurring and human induced peat landslides.

Peat instability, or peat landslides, are a widely documented but relatively rare mechanism of peatland degradation that may result in damage to peatland habitats, potential losses in biodiversity and depletion of peatland carbon stores (Evans & Warburton, 2007). Public awareness of peat landslide hazards increased significantly following three major peat landslide events in 2003, two of which had natural causes and one occurring in association with a wind farm.

On 19th September 2003, multiple peat landslide events occurred in Pollatomish (Co. Mayo, Ireland; Creighton and Verbruggen, 2003) and in Channerwick in the Southern Shetland Islands (Mills et al, 2007). Both events occurred in response to intense rainfall, possibly as part of the same large scale large-scale weather system moving northeast from Ireland across Scotland. The former event damaged several houses, a main road and washed away part of a graveyard. Some of the landslides were sourced from areas of turbary (peat cutting) with slabs of peat detaching along the cuttings. The landslides in Channerwick blocked the main road to the airport and narrowly missed traffic using the road. Watercourses were inundated with peat, killing fish inland and shellfish offshore (Henderson, 2005).

In October 2003, a peat failure occurred on an afforested wind farm site in Derrybrien, County Galway, Ireland, causing disruption to Proposed Development Site and large-scale fish kill in the adjoining watercourses (Lindsay and Bragg, 2004).

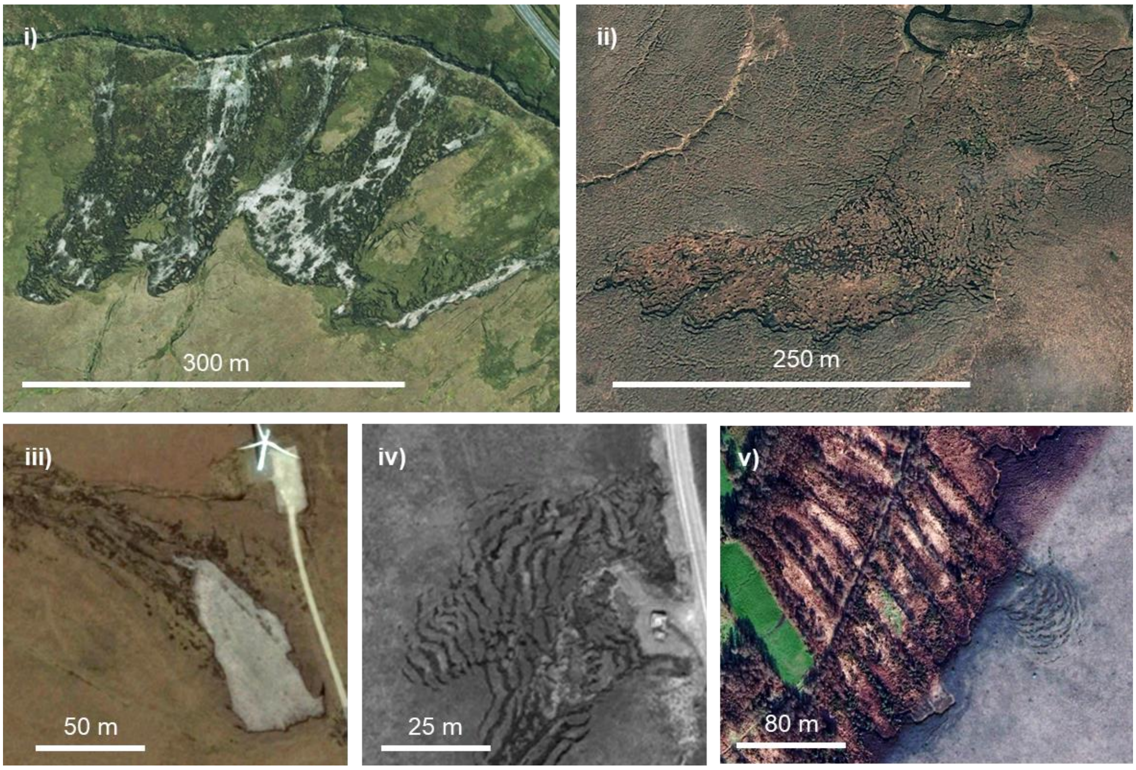
The Derrybrien event triggered interest in the influence of wind farm construction and operation on peatlands, particularly in relation to potential risks arising from construction induced peat instability. In 2007, the (then) Scottish Executive published guidelines on peat landslide hazard and risk assessment in support of planning applications for wind farms on peatland sites. While the production of PLHRA reports is required for all Section 36 energy projects on peat, they are now also regarded as best practice for smaller wind farm applications. The guidance was updated in 2017 (Scottish Government, 2017).

Since then, a number of peat landslide events have occurred both naturally and in association with wind farms (e.g. Plate 8-2-2). In the case of wind farm sites, these have rarely been reported, however landslide scars of varying age are visible in association with wind farm infrastructure on Corry Mountain, Co. Leitrim, at Sonnagh Old Wind Farm, Co. Galway (near Derrybrien; Cullen, 2011), and at Corkey Wind Farm, Co. Antrim. In December 2016, a plant operator was killed during excavation works in peat at the Derrysallagh wind farm site in Co. Leitrim (Flaherty, 2016) on a plateau in which several published examples of instability had been previously reported. A peat landslide was also reported in 2015 near Proposed Development Site of a proposed road for the

Viking Wind Farm on Shetland (The Shetland Times, 2015) though this was not in association with construction works.

Other recent natural events include another failure in Galway at Clifden in 2016 (Irish News, 2016), Cushendall, Co. Antrim (BBC, 2014), in the Glenelly Valley, Co. Tyrone in 2017 (BBC, 2018), Drumkeeran in Co. Leitrim in July 2020 (Irish Mirror, 2020) and Benbrack in Co Cavan in July 2021 (The Anglo-Celt, 2021). Noticeably, the vast majority of reported failures since 2003 have occurred in Ireland and Northern Ireland, with the one reported Scottish example occurring on the Shetland Islands, an area previously associated with peat instability.

Plate 8-2-2: Characteristic peat landslide types in UK and Irish peat uplands: Top row - natural failures: i) multiple peat slides with displaced slabs and exposed substrate, ii) retrogressive bog burst with peat retained within the failed area; Bottom row - failures possibly induced by human activity: iii) peat slide adjacent to turbine foundation, iv) spreading around foundation, v) spreading upslope of cutting



This section of the report provides an overview of peat instability as a precursor to Proposed Development Site characterisation in Section 3 and the hazard and risk assessment provided in Section 4. Section 2.2 outlines the different types of peat instability documented in the UK and Ireland. Section 2.3 provides an overview of factors known to contribute to peat instability based on published literature.

2.2 Types of Peat Stability

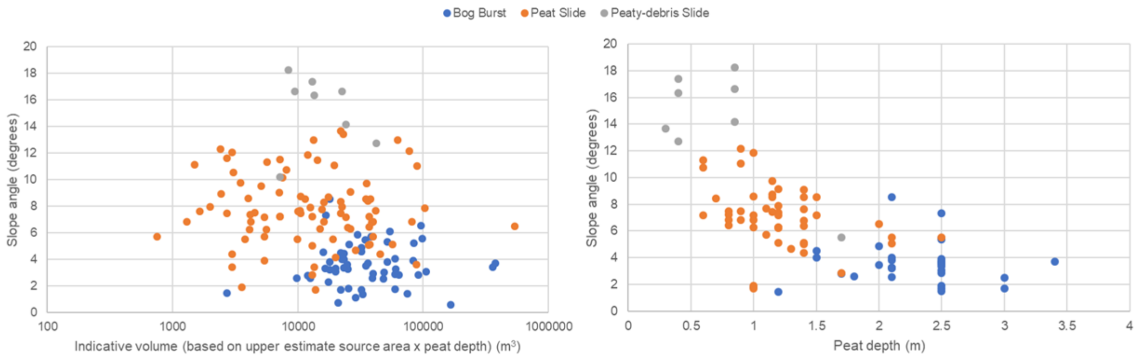
Peat instability is manifested in a number of ways (Dykes and Warburton, 2007) all of which can potentially be observed on site either through site walkover or remotely from high resolution aerial photography:

- **Minor instability:** localised and small-scale features that are not generally precursors to major slope failure and including gully sidewall collapses, pipe ceiling collapses, minor slumping along diffuse drainage pathways (e.g. along flushes); indicators of incipient instability including development of tension cracks, tears in the acrotelm (upper vegetation mat), compression ridges, or bulges / thrusts (Scottish Government, 2017); these latter features may be warning signs of larger scale major instability (such as landsliding) or may simply represent a longer term response of the hillslope to drainage and gravity, i.e. creep; and
- **Major instability:** comprising various forms of peat landslide, ranging from small scale collapse and outflow of peat filled drainage lines/gullies (occupying a few-10s cubic metres), to medium scale peaty-debris slides in organic soils (10s to 100s cubic metres) to large scale peat slides and bog bursts (1,000s to 100,000s cubic metres).

Evans and Warburton (2007) present useful contextual data in a series of charts for two types of large-scale peat instability – peat slides and bog bursts. The data are based on a peat landslide database compiled by Mills (2002) which collates site information for reported peat failures in the UK and Ireland. Separately, Dykes and Warburton (2007) provide a more detailed classification scheme for landslides in peat based on the type of peat deposit (raised bog, blanket bog, or fen bog), location of the failure shear surface or zone (within the peat, at the peat-substrate interface, or below), indicative failure volumes, estimated velocity and residual morphology (or features) left after occurrence.

For the purposes of this assessment, landslide classification is simplified and split into three main types, typical examples of which are shown in Plate 8-2-2. Dimensions, slope angles and peat depths are drawn from charts presented in Evans and Warburton (2007). The term “peat slide” is used to refer to large-scale (typically less than 10,000 of cubic metres) landslides in which failure initiates as large rafts of material which subsequently break down into smaller blocks and slurry. Peat slides occur ‘top-down’ from the point of initiation on a slope in thinner peats (between 0.5m and 1.5m) and on moderate slope angles (typically 5°-15°, see Plate 8-2-3).

Plate 8-2-3: Reported Slope Angles and Peat Depths Associated with Peat Slides and Bog Bursts (from literature review of locations, depths and slope angles, after Mills, 2002)



The term “bog burst” is used to refer to very large-scale (usually greater than 10,000 of cubic metres) spreading failures in which the landslide retrogresses (cuts) upslope from the point of failure while flowing downslope. Peat is typically deeper (greater than 1.0m and up to 10m) and more amorphous than sites experiencing peat slides, with shallower slope angles (typically 2°-5°). Much of the peat displaced during the event may remain within the initial failure zone. Bog bursts are rarely (if ever) reported in Scotland other than in the Western Isles (e.g. Bowes, 1960).

The term “peaty soil slide” is used to refer to small-scale (1,000s of cubic metres) slab-like slides in organic soils (i.e. they are <0.5m thick). These are similar to peat slides in form, but far smaller and occur commonly in UK uplands across a range of slope angles (Dykes and Warburton, 2007). Their small size means that they often do not affect watercourses and their effect on habitats is minimal.

Few if any spreading failures in peat (i.e. bog bursts) have been reported in Scotland, with only one or two unpublished examples in evidence on the Isle of Lewis and Caithness.

There are no published failures or news reports of landslides in proximity to the Proposed Development. Review of the adjacent Craigengelt Wind Farm indicates no instability in association with wind farm infrastructure within a similar setting.

2.2.1 Factors Contributing to Peat Instability

Peat landslides are caused by a combination of factors – triggering factors and reconditioning factors (Dykes and Warburton, 2007; Scottish Government, 2017). Triggering factors have an immediate or rapid effect on the stability of a peat deposit whereas preconditioning factors influence peat stability over a much longer period. Only some of these factors can be addressed by site characterisation.

Preconditioning factors may influence peat stability over long periods of time (years to hundreds of years), and include:

- Impeded drainage caused by a peat layer overlying an impervious clay or mineral base (hydrological discontinuity);
- A convex slope or a slope with a break of slope at its head (concentration of subsurface flow);
- Proximity to local drainage, either from flushes, pipes or streams (supply of water);
- Connectivity between surface drainage and the peat/impervious interface (mechanism for generation of excess pore pressures);
- Artificially cut transverse drainage ditches, or grips (elevating pore water pressures in the basal peat-mineral matrix between cuts and causing fragmentation of the peat mass);
- Increase in mass of the peat slope through peat formation, increases in water content or afforestation;
- Reduction in shear strength of peat or substrate from changes in physical structure caused by progressive creep and vertical fracturing (tension cracking or desiccation cracking), chemical or physical weathering or clay dispersal in the substrate;
- Loss of surface vegetation and associated tensile strength (e.g. by burning or pollution induced vegetation change);
- Increase in buoyancy of the peat slope through formation of sub-surface pools or water-filled pipe networks or wetting up of desiccated areas; and
- Afforestation of peat areas, reducing water held in the peat body, and increasing potential for formation of desiccation cracks which are exploited by rainfall on forest harvesting.

Triggering factors are typically of short duration (minutes to hours) and any individual trigger event can be considered as the final exceedance of a threshold of stability.

- Intense rainfall or snowmelt causing high pore pressures along pre-existing or potential rupture surfaces (e.g. between the peat and substrate);
- Rapid ground accelerations (e.g. from earthquakes or blasting);
- Unloading of the peat mass by fluvial incision or by artificial excavations (e.g. cutting);
- Focusing of drainage in a susceptible part of a slope by alterations to natural drainage patterns (e.g. by pipe blocking or drainage diversion); and
- Loading by plant, spoil or infrastructure.

External environmental triggers such as rainfall and snowmelt cannot be mitigated against, though they can be managed (e.g. by limiting construction activities during periods of intense rain). Unloading of the peat mass by excavation, loading by plant and focusing of drainage can be managed by careful design, site specific stability analyses, informed working practices and monitoring.

2.2.2 Consequences of Peat Instability

Both peat slides and bog bursts have the potential to be large in scale, disrupting extensive areas of blanket bog and with the potential to discharge large volumes of material into watercourses.

A key part of the risk assessment process is to identify the potential scale of peat instability should it occur and identify the receptors of the consequences. Potential sensitive receptors of peat failure are:

- The development infrastructure and turbines (damage to turbines, tracks, substation, etc);
- Site workers and plant (risk of injury / death or damage to plant);
- Wildlife (disruption of habitat) and aquatic fauna;
- Watercourses and lochs (particularly associated with public water supply);
- Site drainage (blocked drains / ditches leading to localised flooding / erosion); and
- Visual amenity (scarring of landscape).

While peat failures may cause visual scarring of the peat landscape, most peat failures revegetate fully within 50 to 100 years and are often difficult to identify on the ground after this period of time (Feldmeyer-Christe and Küchler, 2002; Mills, 2002). Typically, it is short-term (seasonal) effects on watercourses that are the primary concern or impacts on public water supply.

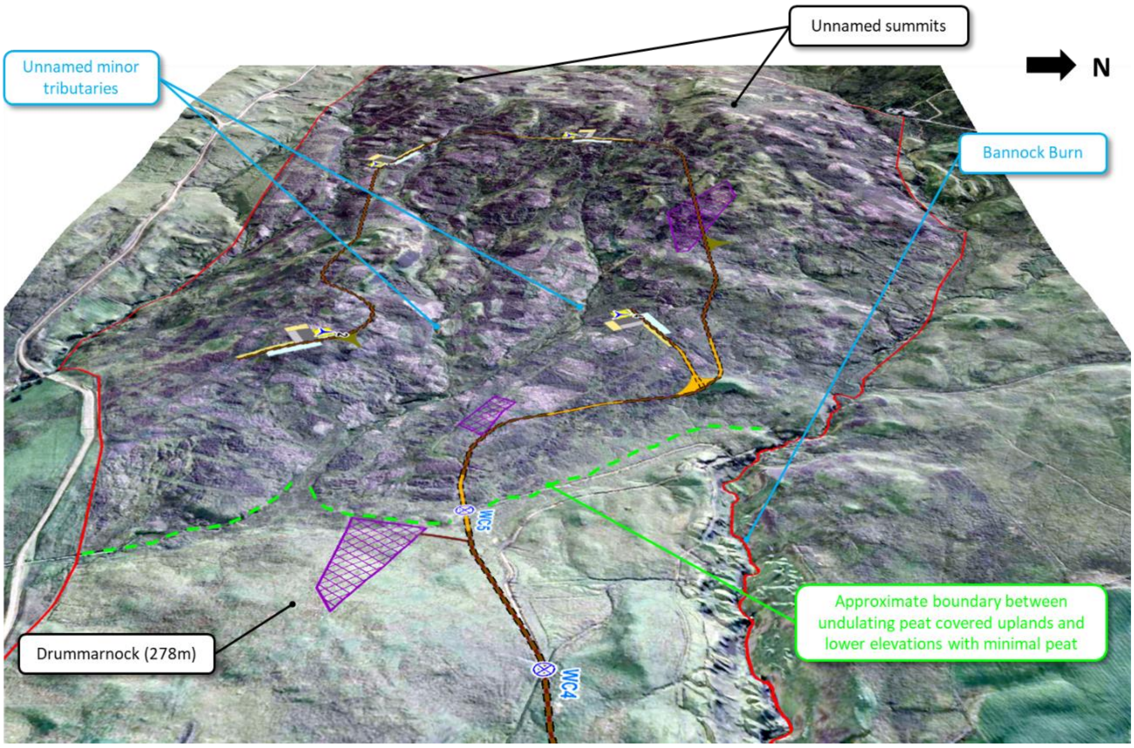
3 Desk Study

3.1 Site Overview

The Proposed Development Site is located over low hills that fall east from a minor road connecting the B818 (in the south) to the Polmaise Road in the north. The highest points (in the west) are two unnamed summits at 373m AOD and 357m AOD, and elevations fall fairly continuously towards the confluence of a series of minor watercourses that deflect south of Drummarnock (278m AOD) (Figure 8-2-1).

Plate 8-2-4 shows a perspective view of the Site with key site features annotated.

Plate 8-2-4: 3D perspective view of the Site with key features annotated (bing imagery © 2024 Microsoft Corporation © Maxar CNES (2024) Distribution Airbus DS)



Slope angles are low to moderate (2.5-7.5°) over the western half of the Proposed Development Site, and locally steep (>10°) around Turbine 2 and along the main access track in the east of the Site. There are few areas of flat or gently sloping (<2.5°) terrain. Figure 8-2-2 shows slope angles across the Proposed Development Site.

The proposed turbines have generally been sited above 270m with tracks running directly upgradient and in parallel to minor watercourses and flushed areas that flow from west to east. The track linking the southern and northern turbines is routed to avoid the headwaters of these watercourses. The easternmost borrow pit lies on the western flank of Drummarnock.

3.2 Geology

Figure 8-2-3 shows the solid geology of the site mapped from 1:50,000 scale publicly available BGS digital data and indicates the majority of the Proposed Development Site to be underlain by basalts of the Gargunnock Hills Lava Member, with a more complex sequence of limestones and quartz-microgabbro in the north east of the site underlying the access track.

The inset panel on Figure 8-2-3 shows the superficial geology of the site, also derived from BGS digital data and shows hummocky glacial till comprised of sand and gravel in the west of the Proposed Development Site and till diamicton in the east. Alluvial deposits are found along the watercourses and peat is shown to have patchy coverage across the western part of the site and locally in the east.

There are no geological designations within the Proposed Development Site.

3.3 Hydrology

Figure 8-2-4 shows the hydrology and geomorphology of the Proposed Development Site. Bannock Burn runs along the northern site boundary to the east, ultimately draining into North Third Reservoir. The reservoir previously supplied drinking water but this was discontinued in 2000 and now hosts recreational trout fishing. However, the entire Proposed Development Site extent lies within a groundwater Drinking Water Protected Area (DWPA).

There are two primary unnamed minor watercourses draining from west-to-east within the Proposed Development Site itself, each with a number of minor confluences (e.g. Plate 8-2-5c). These converge in the lower slopes in the eastern half of the site into an area of widespread artificial drainage to the north of Craigengelt and south of the proposed main access track. These drains then feed into Loch Coulter Reservoir.

Plate 8-2-5: a) active moor drain in west, b) ineffective moor drain, c) unnamed watercourse in east of Site, d) flushed ground with flattened grasses

In the undulating hills in the west of the site, there are a number of flush zones that ultimately become minor watercourses. These are generally rush and grass rich and appear as distinct linear pathways among the wider heather moorland. Typical drainage features are shown on Plates 8-2-5a to d.

3.4 Land Use

Large areas of the undulating peat covered hills have been burnt (Plate 8-2-6), and multiple phases of burning are visible on satellite imagery in Google Earth™.

There is no evidence of cutting for peat on the site and therefore no suitable accommodation space for excavated materials, although in places the heather appears to have been cut in strips rather than burnt.

While there is some limited forestry activity in the east of the site, none of this is within peat soils.

There are no existing quarries within the Proposed Development Site.

Plate 8-2-6: a) typical open rolling moorland in west of Site, b) burned ground, c) typical planar moorland in west of Site, d) diffuse surface water pathway in centre of site

3.5 Peat Depth

Peat depth probing was undertaken by Atmos Consulting in multiple phases between 2021 and December 2023 in accordance with Scottish Government (2017) guidance:

- Phase 1 was undertaken in a number of phases, initially in the main turbine area and then subsequently at lower elevations in the vicinity of potential access tracks – in total c. 230 probes were taken on the 100m grid.
- Subsequent probing focused on refining infrastructure locations using a variety of grid spacings with the final locations assessed using a 10m grid – in total, across Phase 1, interim and final Phase 2 surveys, 2,340 locations were probed.

Interpolation of peat depths was undertaken in the ArcMap GIS environment using a natural neighbour approach. This approach was selected because it preserves recorded depths at each probe location, unlike some other approaches (e.g. kriging) is computationally simple and minimises 'bullseye' effects. The approach was selected after comparison of outputs with three other methods (inverse distance weighting, kriging and TIN).

The interpolated peat depth model is shown on Figure 8-2-5 with probing locations superimposed and layouts shown as wirelines. Peat depth variation can be summarised as follows:

- Peat is relatively widespread over much of the Proposed Development Site, more so in the western half (main infrastructure area) than in the east, where elevations increase.
- While peat is present over much of the main infrastructure area, it is fairly shallow, rarely exceeding 1m in depth, and where it does so, only in isolated pockets – the fragmented and disparate nature of the peatland means that it is difficult to avoid entirely.
- In the eastern half of the site, peat is generally absent, except for a few localised areas typically centred on watercourses (and in which field drains have been cut, though these seem to be fairly ineffective).

The inset map on Figure 8-2-5 shows the Carbon and Peatland (2016) Map, which indicates the Site to comprise Class 4 (area unlikely to be associated with peatland habitats) and Class 5 soils (no peatland habitat recorded) in the western hills and mineral or Class 3 soils (dominant vegetation is not priority peatland habitat) in the east. In contrast, NVC mapping (Chapter 5 of the EIA) for the site shows priority peatland habitats across much of the western half of the site.

3.6 Peatland Geomorphology

Satellite imagery available as an ArcGIS Basemap layer was used to interpret and map features within the site boundary.

Additional imagery from different epochs available on both Google Earth™ and bing.com/maps was also referred to in order to validate the satellite imagery interpretation. A high resolution LIDAR dataset was also available for the western half of the Proposed Development Site which provided helpful additional detail on topography.

The resulting geomorphological map (Figure 8-2-4) was subsequently verified during a site walkover undertaken in November 2022 by a Chartered Geologist / peatland geomorphologist with over 25 years' experience of assessing peat landslides. Plates 8-2-5 and 8-2-6 show typical features identified during the walkovers.

Figure 8-2-4 shows the key features of the site. The presence, characteristics and distribution of these features are helpful in understanding the hydrological function of a peatland, the balance of erosion and peat accumulation (or condition), and the sensitivity of a peatland to potential land-use changes.

The site may be considered as of two halves in terms of character, the western half comprising undulating heather moorland and the east more subdued lowland.

Peat is relatively thin over undulating bedrock, thickening to form planar deposits between local topographic highs. In the upper slopes, flushes emerge from the hillsides, marked by grass and rush ridge areas of vegetation, become minor watercourses in the lower slopes. While sphagnum is locally present, it is not necessarily widespread and heather and grasses dominate.

There is little evidence of erosion in terms of gullying and peat is sufficiently thin that no pipes were identified during walkover. No signs of incipient instability were noted.

In the lower, eastern half of the site, the ground is wet and marshy, in likelihood explaining the relatively wide drainage network that has been cut.

4 Assessment of Peat Landslide Likelihood

4.1 Introduction

This section provides details on the landslide susceptibility and limit equilibrium approaches to assessment of peat landslide likelihood used in this report. The assessment of likelihood is a key step in the calculation of risk, where risk is expressed as follows:

Risk = Probability of a Peat Landslide x Adverse Consequences

The probability of a peat landslide is expressed in this report as peat landslide likelihood and is considered below.

Due to the combination of moderate slopes and low to shallow depth peat at this site, the most likely mode of failure is peat slides, and this is the failure mechanism considered in this report. This is in keeping with the most likely mode of failure for the peat depths and slope angles present at Proposed Development Site (see Plate 8-2-3 and Figures 8-2-5 and 8-2-2).

4.2 Limit Equilibrium Approach

4.2.1 Overview

Stability analysis has been undertaken using the infinite slope model to determine the Factor of Safety (FoS) for a series of 25m x 25m grid cells within the Proposed Development boundary.

This is the most frequently cited approach to quantitatively assessing the stability of peat slopes (e.g. Scottish Government, 2017; Boylan et al, 2008; Evans and Warburton, 2007; Dykes and Warburton, 2007; Creighton, 2006; Warburton et al, 2003; Carling, 1986).

The approach assumes that failure occurs by shallow translational landsliding, which is the mechanism usually interpreted for peat slides. Due to the relative length of the slope and depth to the failure surface, end effects are considered negligible and the safety of the slope against sliding may be determined from analysis of a 'slice' of the material within the slope.

The stability of a peat slope is assessed by calculating a Factor of Safety, F, which is the ratio of the sum of resisting forces (shear strength) and the sum of driving forces (shear stress) (Scottish Government, 2017):

$$F = \frac{c' + (\gamma - h\gamma_w) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta}$$

In this formula c' is the effective cohesion (kPa), γ is the bulk unit weight of saturated peat (kN/m^3), γ_w is the unit weight of water (kN/m^3), z is the vertical peat depth (m), h is the height of the water table as a proportion of the peat depth, β is the angle of the substrate interface (°) and φ' is the angle of internal friction of the peat (°).

This form of the infinite slope equation uses effective stress parameters, and assumes that there are no excess pore pressures, i.e. that the soil is in its natural, unloaded condition. The choice of water table height reflects the full saturation of the soils that would be expected under the most likely trigger conditions, i.e. heavy rain.

Where the driving forces exceed the shear strength (i.e. where the bottom half of the equation is larger than the top), F is < 1, indicating instability. A factor of safety between 1.0 and 1.4 is normally taken in engineering to indicate marginal stability (providing an allowance for variability in the strength of the soil, depth to failure, etc). Slopes with a factor of safety greater than 1.4 are generally considered to be stable.

There are numerous uncertainties involved in applying geotechnical approaches to peat, not least because of its high water content, compressibility and organic composition (Hobbs, 1986; Boylan and Long, 2014).

Peat comprises organic matter in various states of decomposition with both pore water and water within plant constituents, and the frictional particle-to-particle contacts that are modelled in standard geotechnical approaches are different in peats. There is also a tensile strength component to peat which is assumed to be dominant in the acrotelm, declining with increasing decomposition and depth.

As a result, analysis utilising geotechnical approaches is often primarily of value in showing relative stability across a site given credible and representative input parameters rather than in providing an absolute estimate of stability. Representative data inputs have been derived from published literature for drained analyses considering natural site conditions.

4.2.2 Data Inputs

Stability analysis was undertaken in ArcMap GIS software. A 25m x 25m grid was superimposed on the full site extent and key input parameters derived for each grid cell. In total, 7,270 grid cells were analysed. A 25m x 25m cell size was chosen because it is sufficiently small to define a credible landslide size and avoid ‘smoothing’ of important topographic irregularities.

Two forms of analysis have been undertaken:

i. **Baseline stability:** input parameters correspond to undisturbed peat, prior to construction, and under water table conditions typically associated with instability (i.e. full saturation). Effective stress parameters are used in a drained analysis.

ii. **Modified (loaded) stability:** input parameters correspond to disturbed peat, subsequent to construction, with peat loaded by floating track and typical vehicle loads. Total stress parameters are used in this undrained analysis.

Areas where peat has been excavated (e.g. the excavated peat itself and the peat upslope of the excavation) have not been modelled since it is assumed that safe systems of work will include buttressing of / support to excavations.

Table 8-2-1 shows the input parameters and assumptions for the baseline stability analysis. The shear strength parameters c' and φ' are usually derived in the laboratory using undisturbed samples of peat collected in the field and therefore site-specific values are often not available ahead of detailed site investigation for a development.

Therefore, for this assessment, a literature search has been undertaken to identify a range of credible but conservative values for c' and φ' quoted in fibrous and humified peats. FoS analysis was undertaken with conservative φ' of 20° and values of 2 kPa and 5 kPa for c'. These values fall at the low end of a large range of relatively low values (when compared to other soils).

Table 8-2-2 shows the input parameters and assumptions for the modified stability analysis. The analysis employs a 5m wide floating track and assumes representative loads for a multi-axle crane with maximum axle load of 12 t moving over the floated surface.

4.2.3 Results

The outputs of the drained analysis (effective stress) are shown for the best estimate parameter combination on the main panel of Figure 8-2-6. The combination indicates the entire Proposed Development Site to be stable (F >1.4). Use of Low Estimate parameters (inset bottom left of Figure 8-2-6) show only localised pockets of marginal stability on slightly steeper slopes, almost all of which are away from infrastructure.

Table 8-2-1: Geotechnical Parameters for Drained Infinite Slope Analysis

Parameter	Values	Rationale	Source
Effective cohesion (c')	2, 5	Credible conservative cohesion values for humified peat based on literature review	5, basal peat (Warburton et al., 2003) 8.74, fibrous peat (Carling, 1986) 7 - 12, H8 peat (Huat et al, 2014) 5.5 - 6.1, type not stated (Long, 2005) 3, 4, type not stated (Long, 2005) 4, type not stated (Dykes and Kirk, 2001)
Bulk unit weight (γ)	10.5	Credible mid-range value for humified catotelmic peat	10.8, catotelm peat (Mills, 2002) 10.1, Irish bog peat (Boylan et al 2008)
Effective angle of internal friction (φ')	20, 30	Credible conservative friction angles for humified peat based on literature review (only 20° used in analysis)	40 - 65, fibrous peat (Huat et al, 2014) 50 - 60, amorphous peat (Huat et al, 2014) 36.6 - 43.5, type not stated (Long, 2005) 31 - 55, Irish bog peat (Hebib, 2001) 34 - 48, fibrous sedge peat (Farrell & Hebib, 1998) 32 - 58, type not stated (Long, 2005) 23, basal peat (Warburton et al, 2003) 21, fibrous peat (Carling, 1986)
Slope angle from horizontal (β)	Various	Mean slope angle per 25m x 25m grid cell	5m digital terrain model of site
Peat depth (z)	Various	Mean peat depth per 25m x 25m grid cell	Interpolated peat depth model of site
Height of water table as a proportion of peat depth (h)	1	Assumes peat mass is fully saturated (normal conditions during intense rainfall events or snowmelt, which are the most likely natural hydrological conditions at failure)	

The modified crane-loaded assessment for floating track (inset bottom right of Figure 8-2-6) shows all floated track sections to be stable (FoS >1.4) under crane loading bar one 25m cell at the junction to T4. At this location, peat depths drop below 0.5m and therefore peat instability would not occur at a scale of concern in this location.

It should be noted that limit equilibrium methods are not well suited to analysis of peat failures, and therefore in this report, more emphasis is placed on the qualitative likelihood assessment described in Section 4.3).

Table 8-2-2: Geotechnical Parameters and Assumptions for Undrained Infinite Slope Analysis

Parameter	Values	Rationale	Source
Undrained shear strength (Su)	5	Published values show undrained shear strength is typically very similar to effective cohesion (c')	4-30, medium and highly humified (Boylan et al, 2008) 4, more humified (Boylan et al, 2008) 5.2, peat type not stated (Long et al, 2005) 5, Irish bog peat (Farrell and Hebib, 1998)
Bulk unit weight (γ)	10.5	Reduction in volume under floating road is balanced by increased density, so pre-load parameters are used	See Table 8-2-1
Slope angle from horizontal (β)	Various	Credible slope angles for which floating tracks are proposed	See Table 8-2-1
Peat depth (z)	Various	Reduction in volume (i.e. depth) under floating road is balanced by increased density, so pre-load parameters are used	See Table 8-2-1
Crane axle load (t)	12 t	Maximum haul weight that is not considered an "abnormal load"	

4.3 Landslide Susceptibility Approach

4.3.1 Overview

The landslide susceptibility approach is based on the layering of contributory factors to produce unique 'slope facets' that define areas of similar susceptibility to failure. These slope facets vary in size and are different to the regular grid used for the FoS approach. The number and size of slope facets varies from one part of Proposed Development Site to another according to the complexity of ground conditions.

Eight contributory factors are considered in the analysis: slope angle (S), peat depth (P), substrate geology (G), peat geomorphology (M), drainage (D), slope curvature (C), forestry (F), and land use (L). For each factor, a series of numerical scores between 0 and 3 are assigned to factor 'classes', the significance of which is tabulated for each factor.

The higher a score, the greater the contribution of that factor to instability for any particular slope facet. Scores of 0 imply neutral / negligible influence on instability.

Factor scores are summed for each slope facet to produce a peat landslide likelihood score (S_{PL}), the maximum being 24 (8 factors, each with a maximum score of 3).

$$S_{PL} = S_S + S_P + S_G + S_M + S_D + S_C + S_F + S_L$$

In practice, a maximum score is unlikely, as the chance of all contributory factors having their highest scores in one location is very small. The following sections describe the contributory factors, scores and justification for the Proposed Development.

4.3.2 Slope Angle (S)

Table 8-2-3 shows the slope ranges, their association with instability and related scores for the slope angle contributory factor. Slope angles were derived from the 5m digital terrain model shown on Figure 8-2-2 and scores assigned based on reported slope angles associated with peat landslides rather than a simplistic assumption that 'the steeper a slope, the more likely it is to fail' (e.g. Plate 8-2-3).

Table 8-2-3: Slope Classes, Association with Instability and Scores

Slope range (°)	Association with instability	Peat slide
≤2.5	Slope angle ranges for peat slides are based on lower and upper limiting angles for observations of occurrence and increase with increasing slope angle until the upper limiting angle.	0
2.5 - 5.0		1
5.0 – 7.5		3
7.5 - 10.0		3
>10 – 15.0		3
>15.0		3

Figure 8-2-7 shows the distribution of slope angle scores across Proposed Development Site. Slope angle scores are higher in the west of the Site where locally moderate to steep slope angles occur in association with the undulating bedrock-controlled topography.

4.3.3 Peat Depth (P)

Table 8-2-4 shows the peat depths, their association with instability and related scores for the peat depth contributory factor. Peat depth scores were derived from the peat depth model shown on Figure 8-2-5 and reflect the peat depth ranges most frequently associated with peat slides (see Plate 8-2-3).

Table 8-2-4: Peat Depth Classes, Association with Instability and Scores

Peat depth range (m)	Association with instability	Peat slide
>1.5	Bog bursts are the dominant failure mechanism in this depth range where basal peat is more likely to be amorphous	1
0.5 - 1.5	Peat slides are the dominant failure mechanism in this depth range where basal peat is less likely to be amorphous	3
<0.5	Organic soil rather than peat, failures would be peaty-debris slides rather than peat slides or bog bursts and are outside the scope	0

The distribution of peat depth scores is shown on Figure 8-2-7, with the majority of peat being relatively shallow (<1.5m) and therefore being assigned the highest score.

4.3.4 Substrate Geology (G)

Table 8-2-5 shows substrate type, association with instability and related scores for the substrate geology contributory factor. The shear surface or failure zone of reported peat failures typically overlies an impervious clay or mineral (bedrock) base giving rise to impeded drainage.

This, in part, is responsible for the presence of peat, but also precludes free drainage of water from the base of the peat mass, particularly under extreme conditions (such as after heavy rainfall, or snowmelt).

Peat failures are frequently cited in association with glacial till deposits in which an iron pan is observed in the upper few centimetres (Dykes and Warburton, 2007). They have also been observed over glacial till without an obvious iron pan, or over impermeable bedrock. They are rarely cited over permeable bedrock, probably due to the reduced likelihood of peat formation.

Table 8-2-5: Substrate Geology Classes, Association with Instability and Scores

Substrate Geology	Association with instability	Peat slide
Soft clay or iron pan	Failures are often associated with soft clay substrates and/or iron pans	3
Granular clay or clay dominated alluvium	Failures are more frequently associated with substrates with some clay component	2
Granular or bedrock	Failures are less frequently associated with bedrock or granular (silt / sand / gravel) substrates	1

The widespread presence of till of one form or another has been used to assign a moderate score of 2 where till is present (Figure 8-2-7), however, the till is noted to be predominantly sandy to gravelly in composition and this is likely overly conservative.

4.3.5 Peat Geomorphology (M)

Table 8-2-6 shows the geomorphological features typical of peatland environments, their association with instability and related scores.

Table 8-2-6: Peat Geomorphology Classes, Association with Instability and Scores

Geomorphology	Association with instability	Peat slide
Incipient instability (cracks, ridges, bulging)	Failures are likely to occur where pre-failure indicators are present	3
Planar with pipes	Failures generally occur on planar slopes, and are often reported in areas of piping	3
Planar with pools / patterned ground with pools / quaking bog	Bog bursts are more likely in areas of perched water (pools) or subsurface water bodies (quaking bog)	2
Flush / Sphagnum lawn (diffuse drainage)	Peat slides are often reported in association with areas of flushed peat or diffuse drainage	3
Planar (no other features)	Failures generally occur on planar slopes rather than dissected or undulating slopes	2
Peat over undulating bedrock	Failures are rarely reported in areas of peat with frequent rock outcrops	1
Patterned ground / slightly eroded (incl. minor gullies)	Failures are rarely reported in areas with patterned ground, gullying or bare peat	1
Heavily eroded (extensive gullies) / bare peat	Failures are not reported in areas that are heavily eroded or bare	0
Afforested / deforested	Considered within Forestry (F), see below	0

Geomorphology	Association with instability	Peat slide
peatland		

Figure 8-2-7 shows the geomorphological classes from Figure 8-2-4 re-coloured to correspond with Table 8-2-6. Areas of improved or semi-improved grassland have been given a score of 0 (these being largely outside the peat covered parts of the site).

4.3.6 Artificial Drainage (D)

Table 8-2-7 shows artificial drainage feature classes, their association with instability and related scores. Transverse (or contour aligned) / oblique artificial drainage lines may reduce peat stability by creating lines of weakness in the peat slope and encouraging the formation of peat pipes.

A number of peat failures have been identified in published literature which have failed over moorland grips (Warburton et al, 2004). The influence of changes in hydrology becomes more pronounced the more transverse the orientation of the drainage lines relative to the overall slope.

Table 8-2-7: Drainage Feature Classes, Association with Instability and Scores

Drainage Feature	Association with instability	Peat slide
Drains aligned along contours (<15 °)	Drains aligned to contour create lines of weakness in slopes	3
Drains oblique (15-60°) to contour	Most reports of peat slides and bog bursts in association with drainage occurs where drains are oblique to slope	2
Drains aligned downslope (<30° to slope)	Failures are rarely associated with artificial drains parallel to slope or adjacent to natural drainage lines	1
No / minimal artificial drainage	No influence on stability	0

The effect of drainage lines is captured through the use of a 30m buffer on each artificial drainage line (producing a 60m wide zone of influence) present within the peat soils at Proposed Development Site. Each buffer is assigned a drainage feature class based on comparison of the drainage axis with elevation contours (Figure 8-2-7).

4.3.7 Slope Curvature (C)

Table 8-2-8 shows slope (profile) curvature classes, association with instability and related scores. Convex and concave slopes (i.e. positions in a slope profile where slope gradient changes by a few degrees) have frequently been reported as the initiation points of peat landslides by a number of authors.

The geomechanical reason for this is that convexities are often associated with thinning of peat, such that thicker peat upslope applies stresses to thinner 'retaining' peat downslope. Conversely, buckling and tearing of peat may trigger failure at concavities (e.g. Dykes & Warburton, 2007; Boylan and Long, 2011).

However, review of reported peat landslide locations against Google Earth elevation data indicates that the majority of peat slides occur on rectilinear (straight) slopes and that the reporting of convexity as a key driver may be misleading. Accordingly, rectilinear slopes are assigned the highest score.

Table 8-2-8: Slope Curvature Classes, Association with instability and Scores

Profile Curvature	Association with instability	Peat slide
Rectilinear Slope	Peat slides are most frequently reported on rectilinear slopes, while bog bursts are often reported on rectilinear slopes	3
Convex Slope	Peat slides are often reported on or above convex slopes while bog bursts are most frequently associated with convex slopes	2
Concave Slope	Peat failures are occasionally reported in association with concave slopes	1

The 5m digital terrain model and OS contours were used to identify areas of noticeable slope convexity and concavity across Proposed Development Site. Axes of convexity and concavity (running along the contour) were assigned a 50m buffer to produce 100m (upslope to downslope) buffer zones and these were assigned scores in accordance with Table 8-2-8 above.

4.3.8 Forestry (F)

Table 8-2-9 shows forestry classes, their association with instability and related scores. A report by Lindsay and Bragg (2004) on Derrybrien suggested that row alignments, desiccation cracking and loading (by trees) could all influence peat stability.

Table 8-2-9: Forestry Classes, Association with Instability and Scores

Forestry Class	Association with instability	Peat slide
Deforested, rows oblique to slope	Deforested peat is less stable than afforested peat, and inter ridge cracks oblique to slope may be lines of weakness	3
Deforested, rows aligned to slope	Deforested peat is less stable than afforested peat, but slope aligned inter ridge cracks have less impact	2
Afforested, rows oblique to slope	Afforested peat is more stable than deforested peat, but inter ridge cracks oblique to slope may be lines of weakness	2
Afforested, rows aligned to slope	Afforested peat is more stable than deforested peat, but potentially less stable than unforested (never planted) peat	1
Windblown	Windblown trees have full disruption to the underlying peat and residual hydrology due to root plate disturbance	0
Not afforested	No influence on stability	0

Very little of the Proposed Development Site is afforested or has undergone forest preparations except for areas in the far east of the site generally away from proposed infrastructure, where satellite imagery shows the very early stages of new forestry, including ground preparations (see Figure 8-2-7).

4.3.9 Land use (L)

Table 8-2-10 shows land use classes, association with instability and related scores. A variety of land uses have been associated with peat failures (see Section 2.2.1). While it is hypothesised that burning may cause desiccation cracking in peat and facilitate water flows to basal peat (and potential shear surfaces), there is little evidence directly relating burnt ground to peat landslide events.

Table 8-2-10: Land Use Classes, Association with Instability and Scores

Land Use	Association with instability	Peat slide
Machine cutting	Machine cutting may compartmentalise slopes, but has been reported primarily in association with peat slides	3
Quarrying	Quarrying may remove slope support from upslope materials, and has been observed with spreading failures (bog bursts)	2
Hand cutting (turbary)	Hand cutting may remove slope support from upslope materials, and has been reported with raised bog failures	1
Burning (deep cracking to substrate)	Failures are rarely associated with burning, but deep desiccation cracking will have the most severe effects	2
Burning (shallow cracking)	Failures are rarely associated with burning, shallow desiccation cracking will have very limited effects	1
Grazing	Failures have not been associated with grazing, no influence on stability	0

There is evidence of burning over much of Proposed Development Site and this has been scored as 1 (Figure 8-2-7).

4.3.10 Generation of Slope Facets

The eight contributory factor layers shown on Figure 8-2-7 were combined in ArcMap. Scores for each facet were then summed to produce a peat landslide likelihood score. These likelihood scores were then converted into descriptive 'likelihood classes' from 'Very Low' to 'Very High' with a corresponding numerical range of 1 to 5 (in a similar format to the Scottish Government BPG).

Table 8-2-11: Likelihood classes derived from the landslide susceptibility approach

Summed Score from Contributory Factors	Typical site conditions associated with score	Likelihood (Qualitative)	Landslide Likelihood Score
≤ 7	Unmodified peat with no more than low weightings for peat depth, slope angle, underlying geology and peat morphology	Very Low	1
8 - 12	Unmodified or modified peat with no more than moderate or some high scores for peat depth, slope angle, underlying geology and peat morphology	Low	2
13 - 17	Unmodified or modified peat with high scores for peat depth and slope angle and / or high scores for at least three other contributory factors	Moderate	3
18 - 21	Modified peat with high scores for peat depth and slope angle and several other contributory factors	High	4
> 21	Modified peat with high scores for most contributory factors (unusual except in areas with evidence of incipient instability)	Very High	5

Table 8-2-11 describes the basis for the likelihood classes. A judgement was made that for a facet to have a moderate or higher likelihood of a peat landslide, a likelihood score would be required exceeding both the worst-case peat depth and slope angle scores summed (3 in each case, i.e. 3 x 2 classes) alongside three intermediate scores (of 2, i.e. 2 x 3 classes) for other contributory factors.

This means that any likelihood score of 13 or greater would be equivalent to at least a moderate likelihood of a peat landslide. Given that the maximum score attainable is 24, this seems reasonable.

4.3.11 Results

Figure 8-2-8 shows the outputs of the landslide susceptibility approach for peat slides. The results indicate that the majority of the Proposed Development Site has a 'Very Low' or 'Low' likelihood of a peat slide with scattered and localised areas of 'Moderate' likelihood, typically associated with areas of moderate slope.

There are no areas identified with 'High' or 'Very High' landslide likelihood. When compared with the stability analysis approach, the outputs of this approach indicate slightly more of Proposed Development Site to be at lower stability under natural conditions.

4.3.12 Calculated Risk

Both Figures 8-2-6 and 8-2-8 indicate Proposed Development Site to be stable in areas where infrastructure is proposed. In order for there to be a 'Medium' or 'High' risk, likelihoods must be Moderate or higher (see Tables 8-2-12 and 8-2-13 below). This provides a screening basis for the likelihood results.

There are no areas where Factor of Safety (using Best Estimate parameters) is <1.4, nor where the landslide susceptibility approach has calculated Moderate likelihood or greater, and therefore risks cannot exceed Low.

Therefore, a consequence assessment is not required and good practice construction methods should be sufficient to manage and minimise landslide risks. This is considered further in section 5.

Table 8-2-12: Risk ranking as a product of likelihood and consequence

Peat Landslide Likelihood (Score Bracketed)		Adverse Consequence (Scores Bracketed)				
		Very High (5)	High (4)	Moderate (3)	Low (2)	Very Low (1)
	Very High (5)	High	High	Medium	Low	Low
	High (4)	High	Medium	Medium	Low	Negligible
	Moderate (3)	Medium	Medium	Low	Negligible	Negligible
	Low (2)	Low	Low	Low	Negligible	Negligible
	Very Low (1)	Low	Negligible	Negligible	Negligible	Negligible

Table 8-2-13: Suggested action given each level of calculated risk

Score	Risk Level	Action Suggested for Each Zone
17-25	High	Avoid project development at these locations
11-16	Medium	Project should not proceed in MEDIUM areas unless risk can be avoided or mitigated at these locations, without significant environmental impact, in order to reduce risk ranking to LOW or NEGLIGIBLE.
5-10	Low	Project may proceed pending further post-consent investigation in LOW areas to refine risk level and/or mitigate any residual hazards through micro-siting or specific design measures.
1-4	Negligible	Project should proceed with good practice monitoring and mitigation of ground instability/ landslide hazards at these locations as appropriate.

5 Risk Mitigation

5.1 Overview

A number of mitigation opportunities exist to further reduce the risk levels identified at the Proposed Development Site.

These range from infrastructure specific measures (which may act to reduce peat landslide likelihood, and, in turn, risk) to general good practice applied across the Proposed Development Site to engender awareness of peat instability and enable early identification of potential displacement and opportunities for mitigation.

Risks will be mitigated by:

- Post-consent site specific review of the ground conditions in areas of lower stability (Moderate likelihood), which may enable a reduction in likelihood through better understanding, and in turn, further reduction in risk; and
- Precautionary construction measures – including use of monitoring, good practice and a geotechnical risk register relevant to all locations.

Based on the analysis presented in this report, risks are no higher than "Low" or "Negligible" across the Proposed Development Site, and site-specific mitigation is not required to reduce risks pre-consent. Sections 5.2 to 5.4 provide information on good practice pre-construction, during construction and post-construction (i.e. during operation).

5.2 Good Practice Prior to Construction

Site safety is critical during construction, and detailed intrusive site investigation and laboratory analysis will be undertaken ahead of the construction period in order to characterise the strength of the peat soils in the areas in which excavations are proposed, particularly where these fall in areas of Low or greater likelihood. These investigations should be sufficient to:

1. Determine the strength of free-standing bare peat excavations;
2. Determine the strength of loaded peat (where excavators and plant are required to operate on floating hardstanding or track, or where operating directly on the bog surface); and
3. Identify sub-surface water-filled voids or natural pipes delivering water to the excavation zone, e.g. through the use of ground penetrating radar or careful pre-excavation site observations.

A comprehensive Geotechnical Risk Register will be prepared post-consent but pre-construction detailing sequence of working for excavations, measures to minimise peat slippage, design of retaining structures for the duration of open hole works, monitoring requirements in and around the excavation and remedial measures in the event of unanticipated ground movement.

The risk register will be considered a live document and updated with site experience as infrastructure is constructed. Ideally, a contractor with experience of working in deep peat will be engaged to undertake the works.

5.3 Good Practice During Construction

The following good practice will be undertaken during construction:

For excavations:

- Use of appropriate supporting structures around peat excavations (e.g. for turbines, crane pads and compounds) to prevent collapse and the development of tension cracks;
- Avoid cutting trenches or aligning excavations across slopes (which may act as incipient back scars for peat failures) unless appropriate mitigation has been put in place;
- Implement methods of working that minimise the cutting of the toes of slope, e.g. working up-to-downslope during excavation works;
- Monitor the ground upslope of excavation works for creep, heave, displacement, tension cracks, subsidence or changes in surface water content;
- Monitor cut faces for changes in water discharge, particularly at the peat-substrate contact; and
- Minimise the effects of construction on natural drainage by ensuring that natural drainage pathways are maintained or diverted such alteration of the hydrological regime of Proposed Development Site is minimised or avoided; drainage plans should avoid creating drainage/infiltration areas or settlement ponds towards the tops of slopes (where they may act to both load the slope and elevate pore pressures).

For cut tracks:

- Maintain drainage pathways through tracks to avoid ponding of water upslope;
- Monitor the top line of excavated peat deposits for deformation post-excavation; and
- Monitor the effectiveness of cross-track drainage to ensure water remains free-flowing and that no blockages have occurred.

For floating tracks:

- Allow peat to undergo primary consolidation by adopting rates of road construction appropriate to weather conditions;
- Identify 'stop' rules, i.e. weather dependent criteria for cessation of track construction based on local meteorological data;
- Run vehicles at 50% load capacity until the tracks have entered the secondary compression phase; and
- Prior to construction, setting out the centreline of the proposed track to identify any ground instability concerns or particularly wet zones.

For storage of peat and for restoration activities:

- Ensure stored peat is not located upslope of working areas or adjacent to drains or watercourses;
- Undertake site specific stability analysis for all areas of peat storage (if on sloping ground) to ensure the likelihood of destabilisation of underlying peat is minimised;
- Where possible, avoid storing peat on slope gradients >3° and preferably store on ground with neutral slopes and natural downslope barriers to peat movement;

- Monitor effects of wetting / re-wetting stored peat on surrounding peat areas, and prevent water build up on the upslope side of peat mounds;
- Undertake regular monitoring of emplaced peat in restoration areas to identify evidence of creep or pressure on retaining structures (dams and berms); and
- Maximise the interval between material deliveries over newly constructed tracks that are still observed to be within the primary consolidation phase.

In addition to these control measures, the following good practice will be followed:

- The geotechnical risk register prepared prior to construction will be updated with site experience as infrastructure is constructed;
- Full site walkovers will be undertaken at scheduled intervals to be agreed with the Local Authority to identify any unusual or unexpected changes to ground conditions (which may be associated with construction or which may occur independently of construction);
- All construction activities and operational decisions that involve disturbance to peat deposits will be overseen by an appropriately qualified geotechnical engineer with experience of construction on peat sites;
- Awareness of peat instability and pre-failure indicators will be incorporated in site induction and training to enable all site personnel to recognise ground disturbances and features indicative of incipient instability;
- A weather policy will be agreed and implemented during works, e.g. identifying 'stop' rules (i.e. weather dependent criteria) for cessation of track construction or trafficking and
- Monitoring checklists will be prepared with respect to peat instability addressing all construction activities proposed for site.

It is considered that taken together, these mitigation measures should be sufficient to reduce risks to construction personnel to Negligible by reducing consequences to minor injury or programme delay (i.e. Moderate consequences) with a Very Low likelihood of occurrence.

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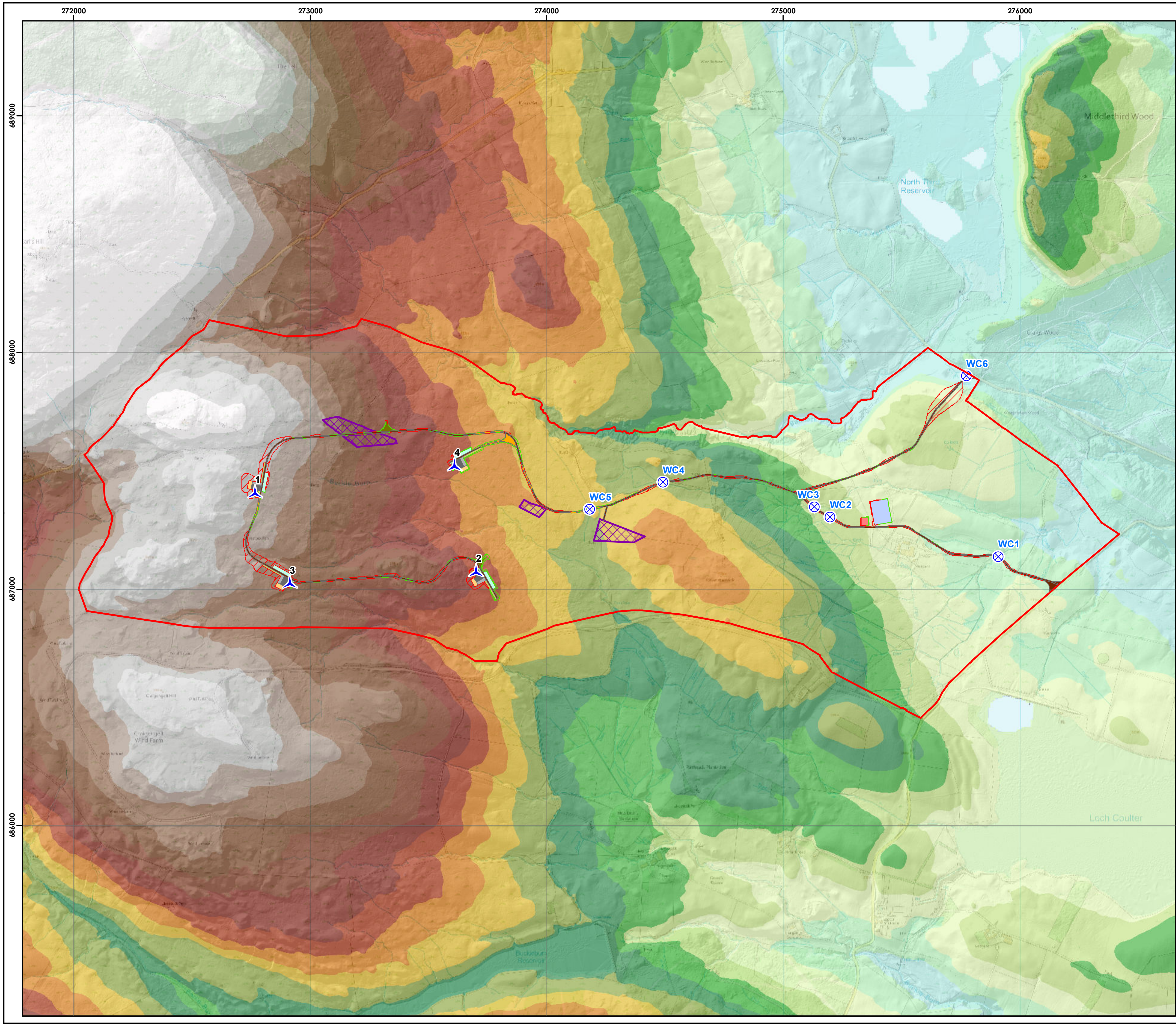

Drummarnock Wind Farm

wind2

Figure 8.2.1
Elevation

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Earthworks - cut
- Earthworks - fill
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Elevation (m)

< 200	280 - 290
200 - 210	290 - 300
210 - 220	300 - 310
220 - 230	310 - 320
230 - 240	320 - 330
240 - 250	330 - 340
250 - 260	340 - 350
260 - 270	350 - 360
270 - 280	> 360

EAST POINT GEO
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0 125 250 500
Metres

N

Scale @ A3:
1:15,000

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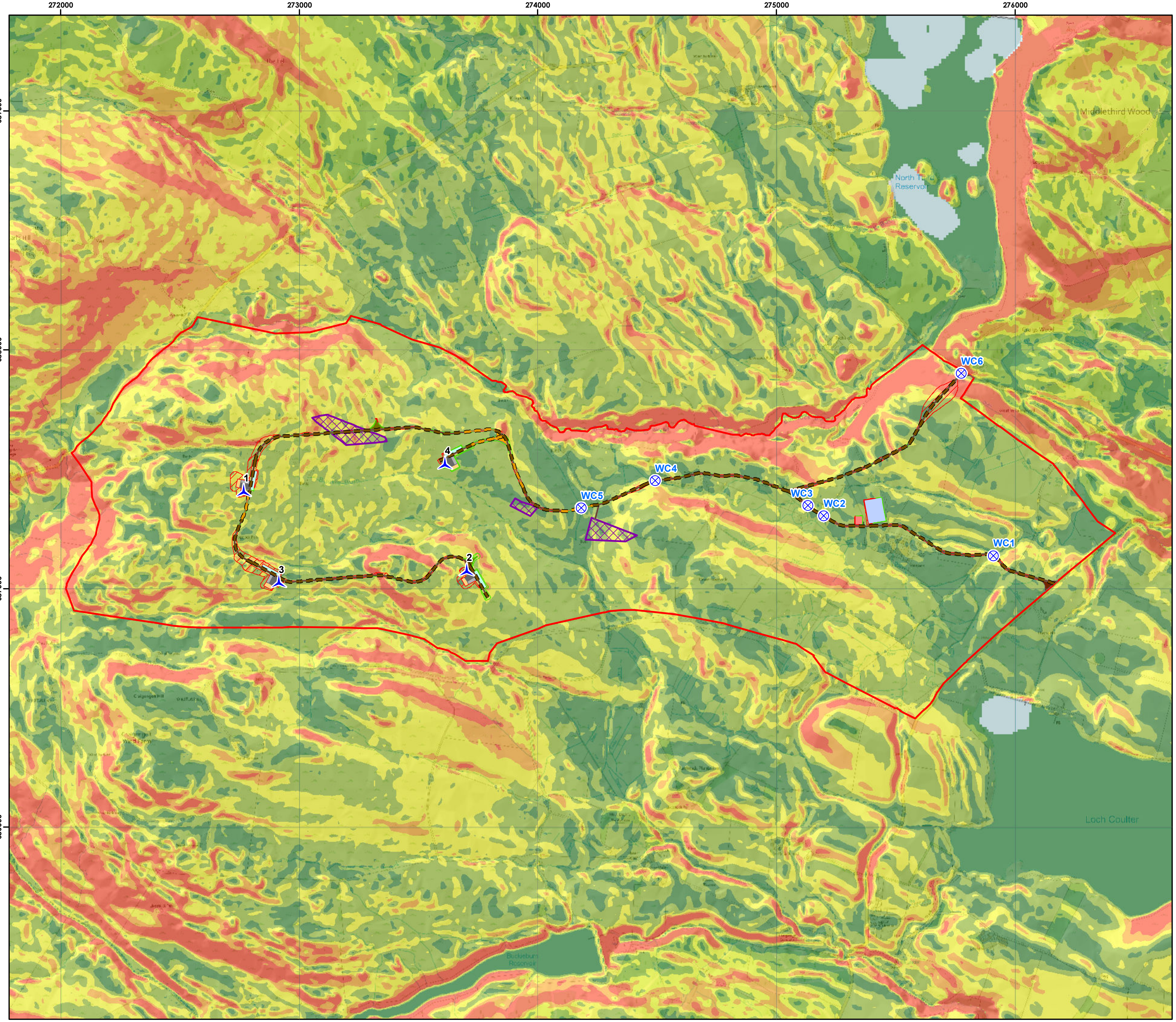
Drawn by: AM	Checked by: LK	Approved by: LK



Drummarnock Wind Farm

wind2

Figure 8.2.2
Slope Angle

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Earthworks - cut
- Earthworks - fill
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Slope angle (degrees)

- 0.0 - 2.5
- 2.5 - 5.0
- 5.0 - 7.5
- 7.5 - 10.0
- >10.0

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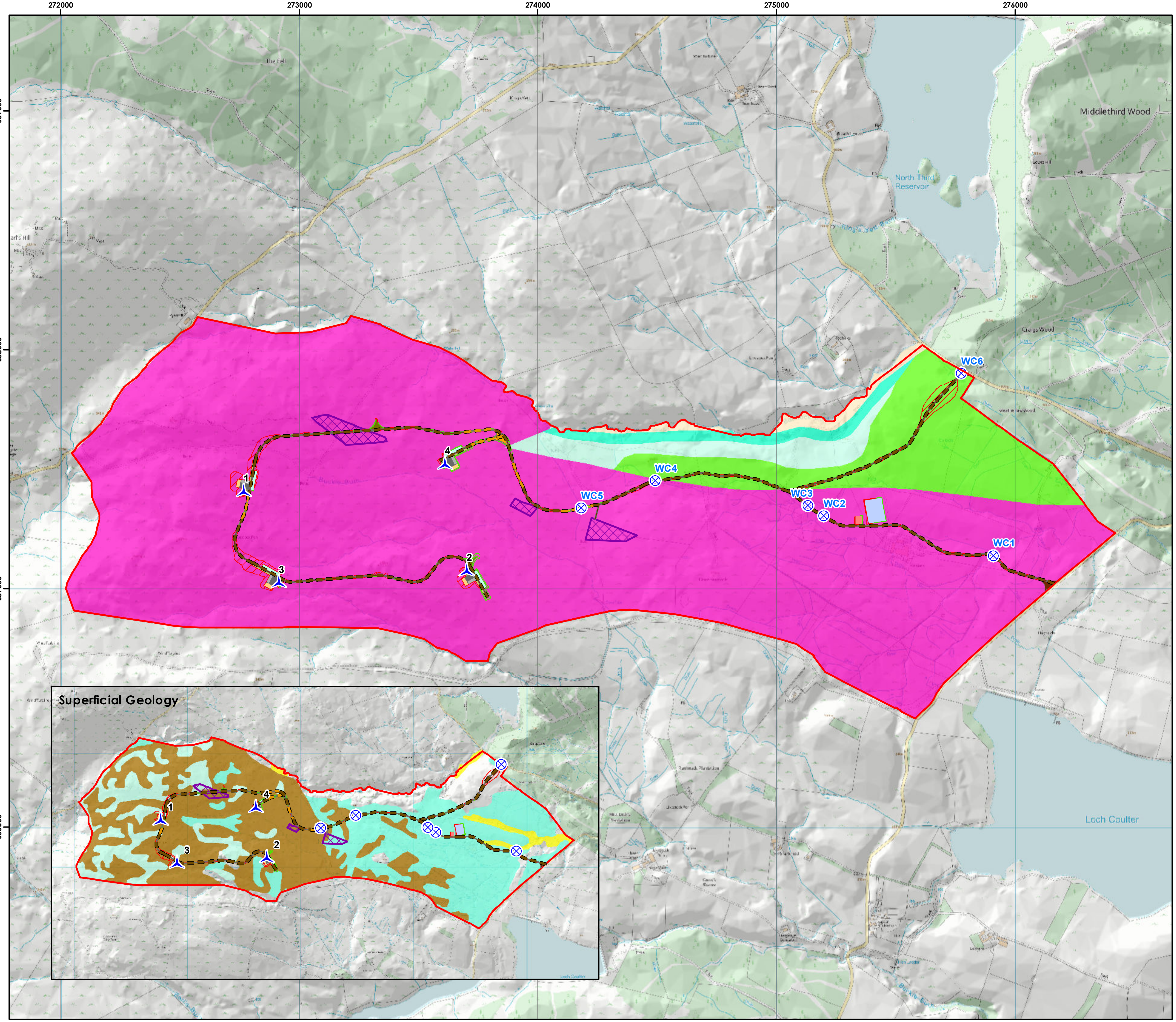

Drummarnock Wind Farm

wind2

Figure 8.2.3
Geology

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

BedrockGeology

- Midland Valley Sill-complex - Quartz-microgabbro
- Gargunnock Hills Lava Member - Basaltic-rock, plagioclase-macrophyric
- Hurlet Limestone
- Lawmuir Formation - Strathclyde Group
- Lower Limestone Formation - Clackmannan Group

Superficial Geology (inset)

- Hummocky (moundy) Glacial Deposits - Diamicton, sand and gravel
- Till, Devensian - Diamicton
- Alluvium - Clay, silt, sand and gravel
- Peat

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0 125 250 500
Metres

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Scale @ A3:
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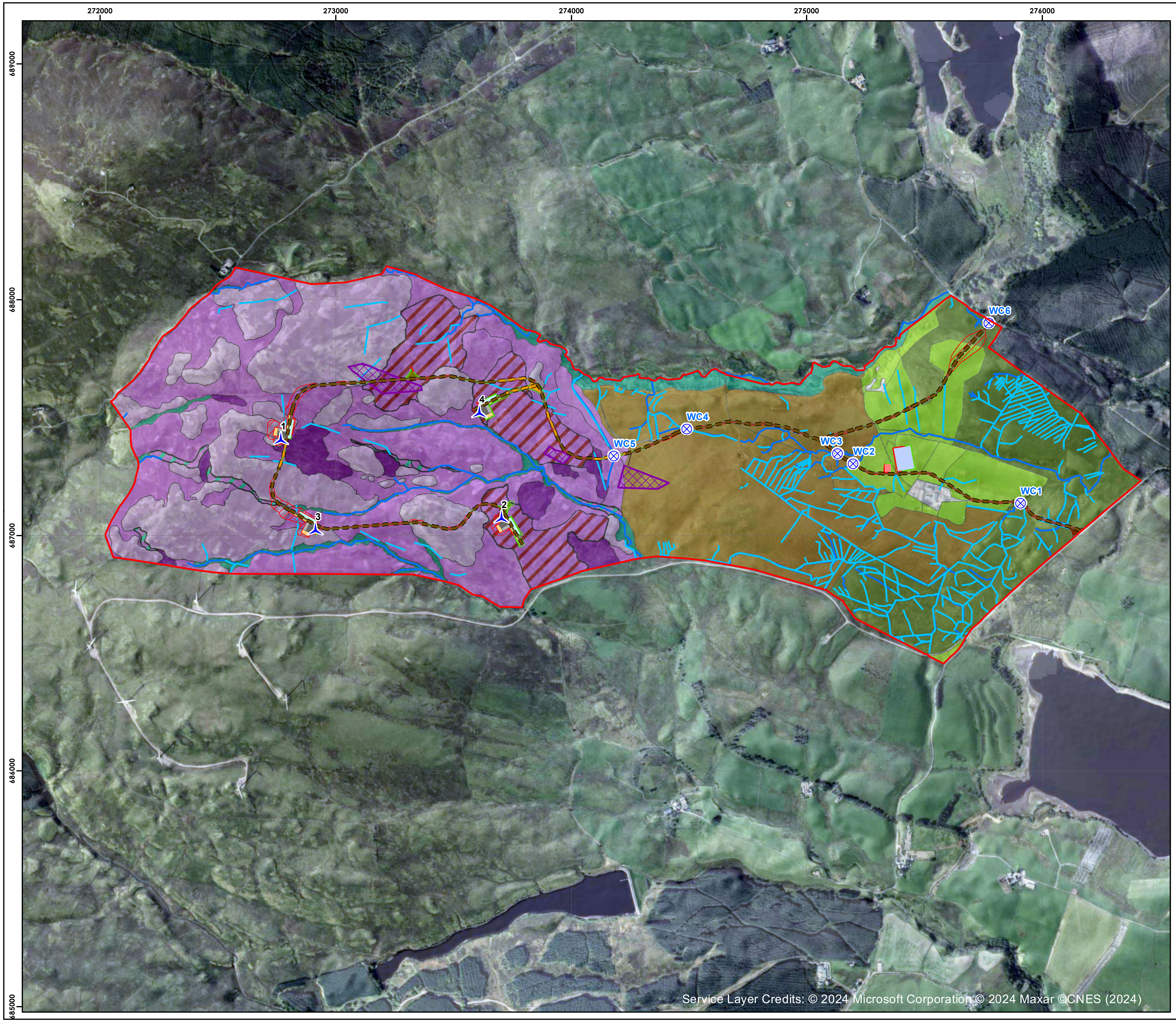

Drummarnock Wind Farm

wind2

Figure 8.2.4
Geomorphology, hydrology and land use

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Geomorphology, hydrology and land use

- Peat over undulating bedrock
- Planar peat
- Flush
- Planar peat (heather cutting)
- Patterned ground
- Newly afforested
- Improved ground
- Unimproved ground
- Made ground
- Drains
- Watercourses
- Water body
- Gully / Watercourse

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0 125 250 500
Metres

N

Scale @ A3:
1:15,000

28/03/24	Turbine layout 26	Drawing number
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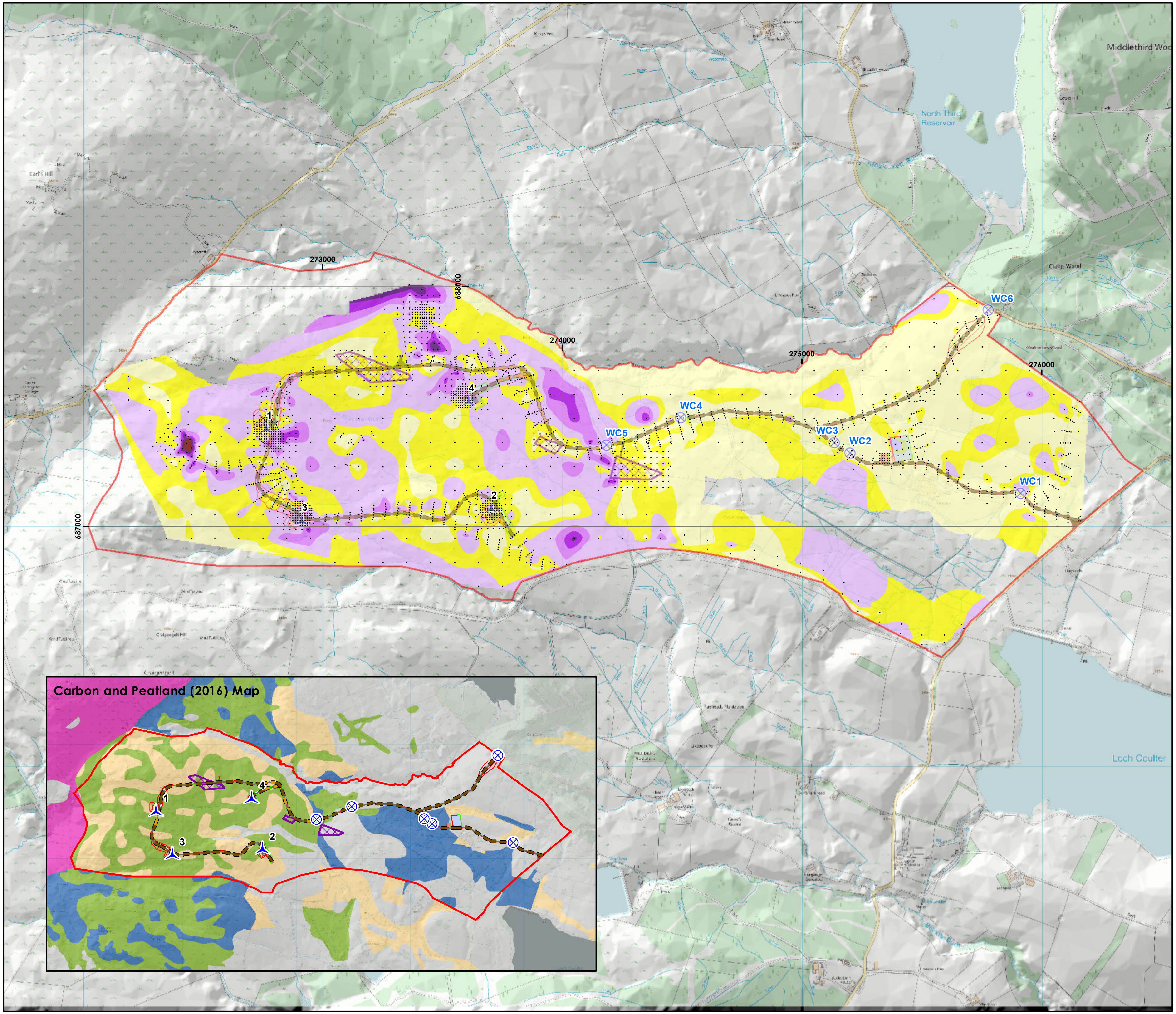

Drummarnock Wind Farm

wind2

Figure 8.2.5
Peat Depth

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Earthworks - cut
- Earthworks - fill
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Peat depth (m)

- 0.0 - 0.3 (soil)
- 0.3 - 0.5 (soil)
- 0.5 - 1.0 (peat)
- 1.0 - 1.5 (peat)
- 1.5 - 2.0 (peat)
- 2.0 - 2.5 (peat)
- >2.50 (peat)
- Probe location

Carbon and Peatland (2016) Map (inset)

- Class 1
- Class 2
- Class 3
- Class 4
- Class 5
- Mineral Soil
- Unknown Soil
- Non Soil

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0 125 250 500
Metres

N

Scale @ A3:
1:15,000

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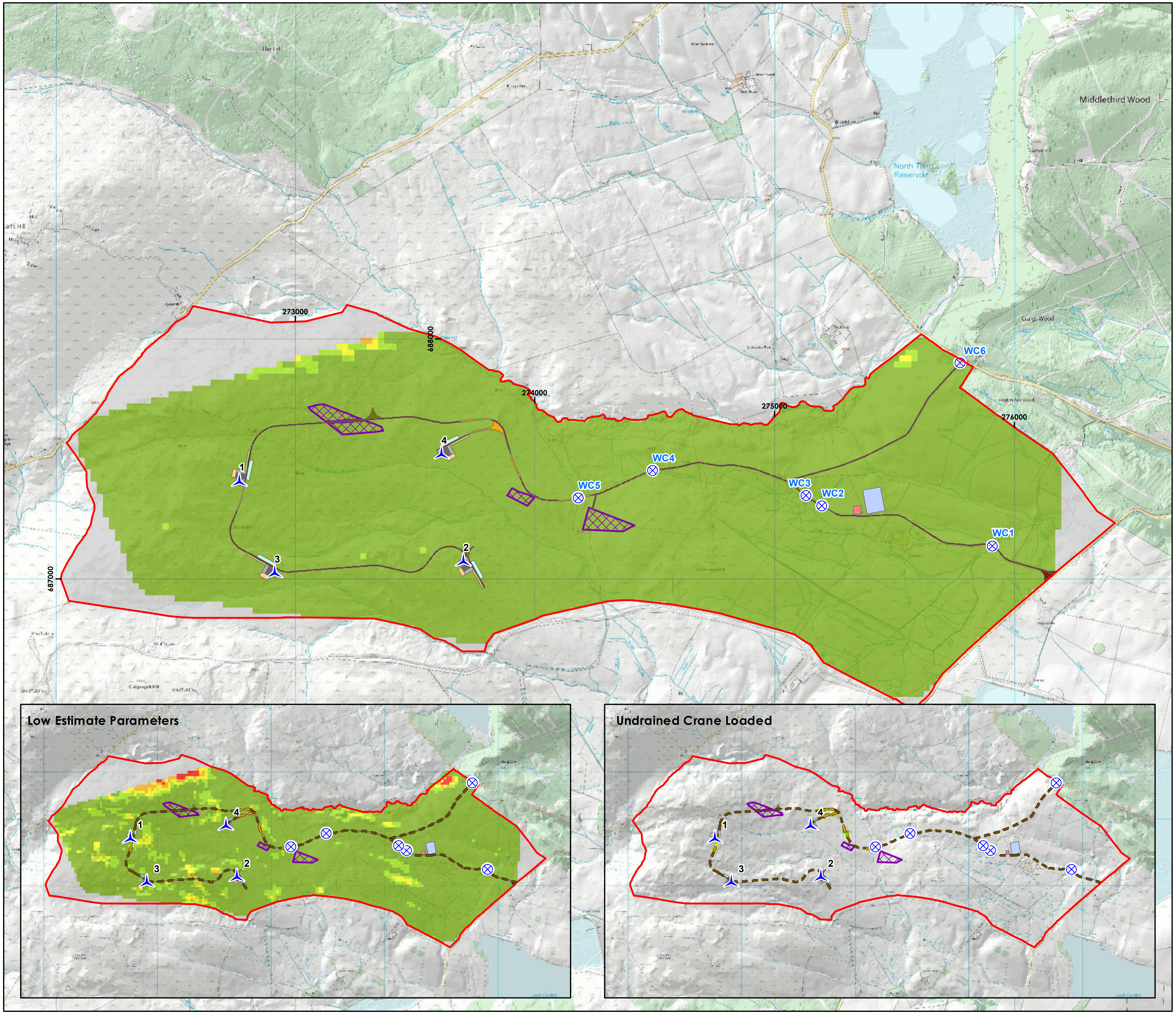

Drummarnock Wind Farm

wind2

Figure 8.2.6
Factor of Safety

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Earthworks - cut
- Earthworks - fill
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Factor of Safety

- Unassessed
- 0.0 - 1.0 (Unstable)
- 1.0 - 1.4 (Marginally stable)
- 1.4 - 2.0 (Stable)
- 2.0 - 3.0 (Stable)
- >3.0 (Stable)

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0 125 250 500
Metres

N

Scale @ A3:
1:15,000

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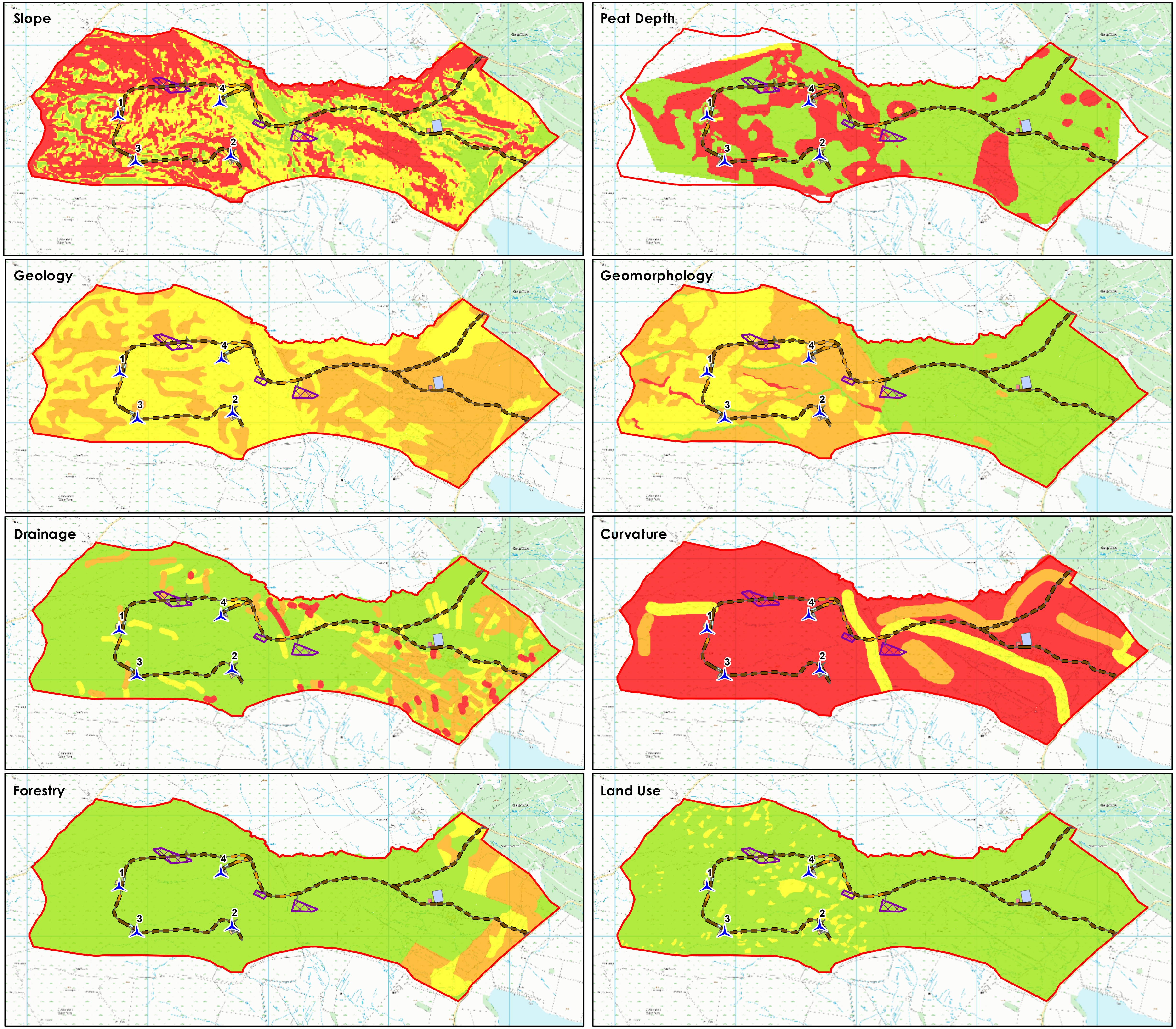

Drummarnock Wind Farm

wind2

Figure 8.2.7
Contributory factors

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Earthworks - cut
- Earthworks - fill
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Score

- 0
- 1
- 2
- 3

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0 125250 500
Metres

N

Scale @ A3:
1:30,000

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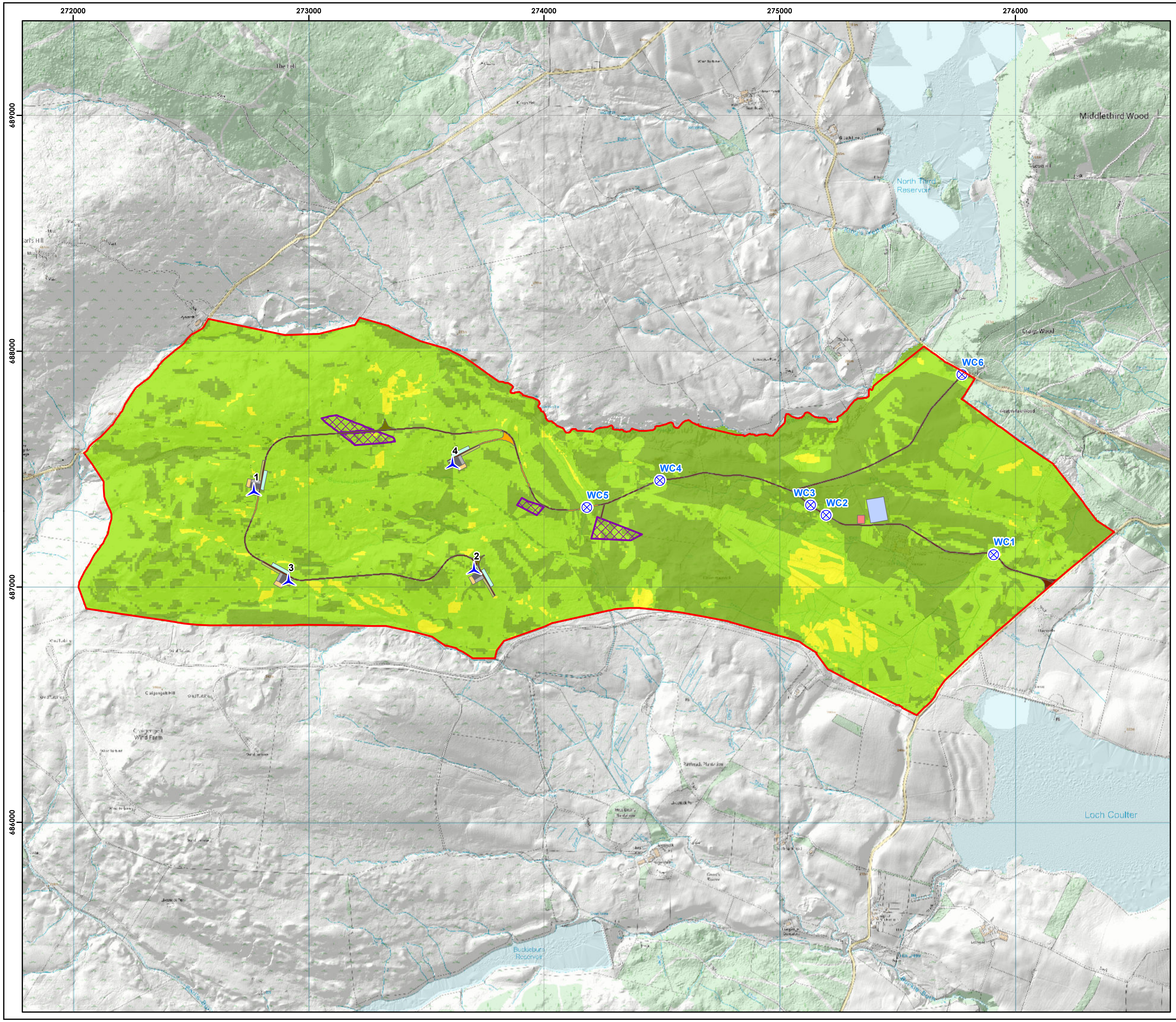

Drummarnock Wind Farm

wind2

Figure 8.2.8
Likelihood

Key

- Site boundary
- Turbines
- Turbine foundation
- Crane hardstanding
- Auxiliary crane hardstanding
- Blade storage area
- Nacelle storage area
- Tower storage area
- Boom assembly area
- Turning head
- Onsite access track - cut
- Onsite access track - floating
- Onsite access track - upgraded
- Earthworks - cut
- Earthworks - fill
- Borrow pit
- Substation
- Construction compound
- Watercourse crossing - Existing
- Watercourse crossing

Contributory Scores

- 0 - 7 (Very Low)
- 8 - 12 (Low)
- 13 - 16 (Moderate)
- 17 - 21 (High, none calculated)
- 22 - 24 (Very High, none calculated)

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0 125 250 500
Metres

N

Scale @ A3:
1:15,000

28/03/24	Turbine layout 26	Drawing number
Drawn by: AM	Checked by: LK	Approved by: LK