Investigation of the Wind Power Potential in Scotland

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GitHub Repository

- **GitHub Link:** https://github.com/2662474984/MyFirstRepo.git

Declaration

> In submitting this assignment, I hereby confirm that I have read the University's statement on Good Academic Practice. The following work is my own. Significant academic debts and borrowings have been properly acknowledged and referenced.

Introduction

Renewable energy has grown increasingly important in recent decades, as global warming has become an urgent challenge requiring a transformation in energy sources. Scotland, in particular, has announced a strong commitment to transforming 100% of electricity consumption into renewable sources. Up until 2020, this figure had reached 98.8% (Scottish Government, 2022). However, electricity demand in Scotland is expected to double over the next two decades, driven by the electrification of heating and transport. Meeting this demand while maintaining a high proportion of clean energy will require a strategy that substantially expands renewable energy generation capacity.

Onshore wind remains the most significant contributor to Scotland's energy supply. Previous studies have shown that Scotland has the highest potential for wind energy, given its relatively smaller land area compared to England (Harper et al., 2019). There are currently 8.7GW of onshore wind farms installed in Scotland, but projections suggest that, given the current rising trend in energy demand, a minimum capacity of 20GW of onshore wind farms is required by 2030. Therefore, identifying suitable locations for new wind farms shall be the priority.

Although some studies have examined the distribution of existing wind turbines, few national-scale assessments directly compare modelled suitability with the spatial pattern of operational wind farms. Furthermore, proximity to the electricity grid—a major determinant of economic feasibility—has been underrepresented in earlier work, despite its particular importance in Scotland's more remote regions.

This study, therefore, aims to develop a national-scale suitability index for onshore wind development in Scotland by integrating factors related to wind resource potential, feasibility, grid accessibility, and land-use constraints. The result is compared with the locations of existing onshore wind turbines to assess how well current development patterns align with modelled suitability. Based on this comparison, recommendations for future wind farm siting are proposed, and the performance of the suitability modelling approach is evaluated in terms of its agreement with real-world turbine locations.

Methodology

Criterion & constraint data

The factors incorporated to assess the suitability of wind farms were informed by Wimhurst, Nsude and Greene's (2023) systematic review of GIS-based wind energy studies. Across the literature, the most frequently included criteria are wind speed, distance to roads, slope, and distance to the transmission network. A land-use constraint is further incorporated to remove areas unsuitable for a wind farm. Because the aim of this study is to evaluate broad, Scotland-wide suitability rather than a site-specific assessment, some fine-scaled criteria, such as distance to airport, are not included. The criterion and data source are summarised in Table 1.

According to previous studies that applied the analytic hierarchy process (AHP) to rank the relative importance of the criteria, wind speed is the primary determinant of electricity generation potential, and a positive correlation with energy yield is expected. A weight of 50% is assigned to wind speed. Slope affects construction costs and turbine stability, as steep terrain increases foundation requirements and access difficulty. Hence, slope is assigned a weight of 30% with lower slopes considered more suitable. Both the power grid and main roads are crucial infrastructure for wind farm construction and electricity transmission. However, only major high-voltage grids and main roads are represented in the study due to computational limitations. Hence, the two criteria are assigned a minor weight, with higher suitability corresponding to shorter distance (Yousefi, Motlagh and Montazeri, 2022).

Method 1: MCE in QGIS

The multi-criteria evaluation (MCE) was carried out in QGIS. All raster layers were reprojected to a 500 m resolution to ensure consistency. Vector datasets, including the power grid and road network, were rasterised prior to analysis. The Great Britain road link layer was clipped to the extent of Scotland, after which only the "A Roads", which represent the main roads, were subset from the attribute table. Distance-to-road and distance-to-grid layers were generated using the Proximity tool, while slope was derived from the elevation raster using the Terrain Analysis tool.

According to Scottish Natural Heritage (2017), settlements and buildings within a landscape tend to be sensitive to the development of a wind farm. In addition, although some wind projects in Scotland are located in woodland areas, woodland was treated as a constraint in this study due to the complex forest type and the unpredictable ecological impact of tree-felling. The decision will likely lead to an underestimation of the number of feasible wind farm sites. Overall, urban areas, woodland and water bodies were excluded from the evaluation. Finally, a layer of current operational onshore wind turbines was overlaid on the suitability index for comparison. Suitability values at turbine locations were extracted using the Sample Raster Values tool for subsequent comparison.

*Table 1. The criteria and constraint used in MCE along with individual weight and data sources. *

Criterion & constraint	Weight	Data	Source
Criterion 1: Wind speed	50%	Scotland 1km resolution wind-speed at 10m above ground	https://globalwindatlas.info/en/
Criterion 2: Slope	30%	Scotland 500m-resolution DEM	https://digimap.edina.ac.uk/
Criterion 3: Proximity to power grid	10%	Scotland over-head grid and super grid shapefile	https://ssentransmission.opendatasoft.com/register/
Criterion 4: Proximity to major road	10%	Great Britain road link shapefile	https://digimap.edina.ac.uk/
Constraint: Landuse	-	Ordnance Survey Land Use Feature collection 1km resolution	https://osdatahub.os.uk/data/downloads/sample/NgdLandUseFeatures

Method 2: Comparison in Python

Python was used to analyse the relationship between the suitability index and the locations of existing onshore wind turbines. The suitability value of every pixel across Scotland was extracted from the raster and visualised using a histogram to illustrate the overall distribution. To further evaluate the relationship, the suitability index was classified into four categories, from “very low” to “very high,” using quantile-based classification. A pie chart was subsequently plotted to visualise the proportions of turbines in each category, in order to show whether current turbine siting aligns with areas identified by the MCE model as highly suitable.

Results

Figure 1 shows the administrative map of Scotland. The result will be described and discussed, referring to the council areas on the map.

Figure 2 shows the wind speed criterion (left) and slope criterion (right). The areas with the highest wind speeds cluster in north-west Scotland, especially in the western Scottish Highlands and Argyll and Bute, with some extending into western Aberdeenshire and northern Perth and Kinross. There are also smaller patches of higher wind speeds in southern Scotland, such as in the Scottish Borders. Scotland's Central Belt has a moderate overall wind speed. On the other hand, the slope criterion displays an exactly opposite pattern. Flat lands are located along the eastern coast of Scotland, including the north-most area of Highland, Eastern Aberdeenshire, Fife, as well as the majority of the Central Belt. The main islands, Shetland, Orkney, and the Outer Hebrides, are also dominated by flat areas.

Figure 3 shows the raster of the suitability index (left) and the overlap with existing turbines (right). By combining all the criteria and land-use constraints, areas with the highest suitability index are distributed mainly in the northeast and central Highlands near Inverness, Eastern Aberdeenshire, the Central Belt, south-western Dumfries and Galloway, Orkney, the Hebrides, and some islands in south-western Argyll & Bute.

Figure 4 shows the distribution of suitability in each raster pixel across Scotland. There are quite a significant number of pixels with a suitability of 0 due to land-use constraints. The suitability of the rest of the area clusters at 0.6 with very few pixels greater than 0.8 or less than 0.4.

Figure 5 shows the current wind turbines within each suitability category. The majority of the turbines are located in high-suitability (28.5%) and very-high-suitability (46.1%) categories. However, there is also an indispensable proportion of turbines within the very-low-suitability (12.8%) group, which will be interpreted in the discussion section.


NORTH
ATLANTIC
OCEAN
NORTH
SEA
Shetland
Lerwick
Orkney
Kirkwall
Outer
Hebrides
Stornoway
Highland
Inverness
Elgin
Moray
Aberdeenshire
Aberdeen
Angus
Forfar
Dundee
Perth and Kinross
Perth
Fife
Glenrothes
Stirling
Clackman-
nanshire
Alloa
Argyll and Bute
Lochgilphead
Dumbarton
East
Dunbar-
tonshire
Falkirk
EDINBURGH
Haddington
East Lothian
Dalkeith
Midlothian
Greenock
Paisley
Glasgow
Kirkintilloch
Livingston
West
Lothian
Motherwell
Giffnock
North
Ayrshire
Irvine
Kilmarnock
East
Ayrshire
Hamilton
South
Lanark-
shire
Newtown
St Boswells
Scottish Borders
Ayr
South
Ayrshire
Dumfries and Galloway
Dumfries
IRELAND
Northern
Ireland
England
1 East Renfrewshire
2 Inverclyde
3 North Lanarkshire
4 Renfrewshire
5 West Dunbartonshire

Figure 1. Scotland administrative map.

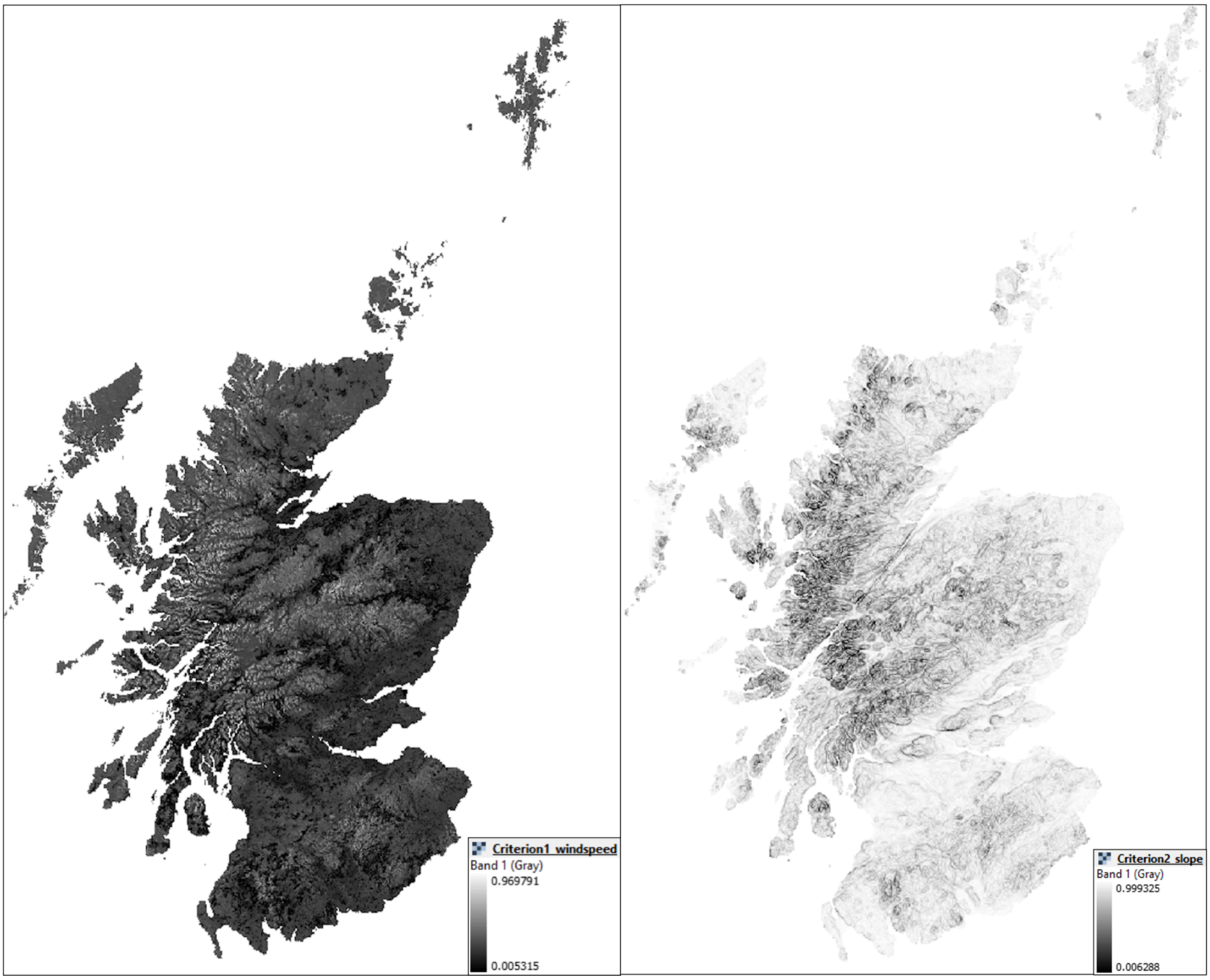


Figure 2. Windspeed criterion result (left) and slope criterion result (right).

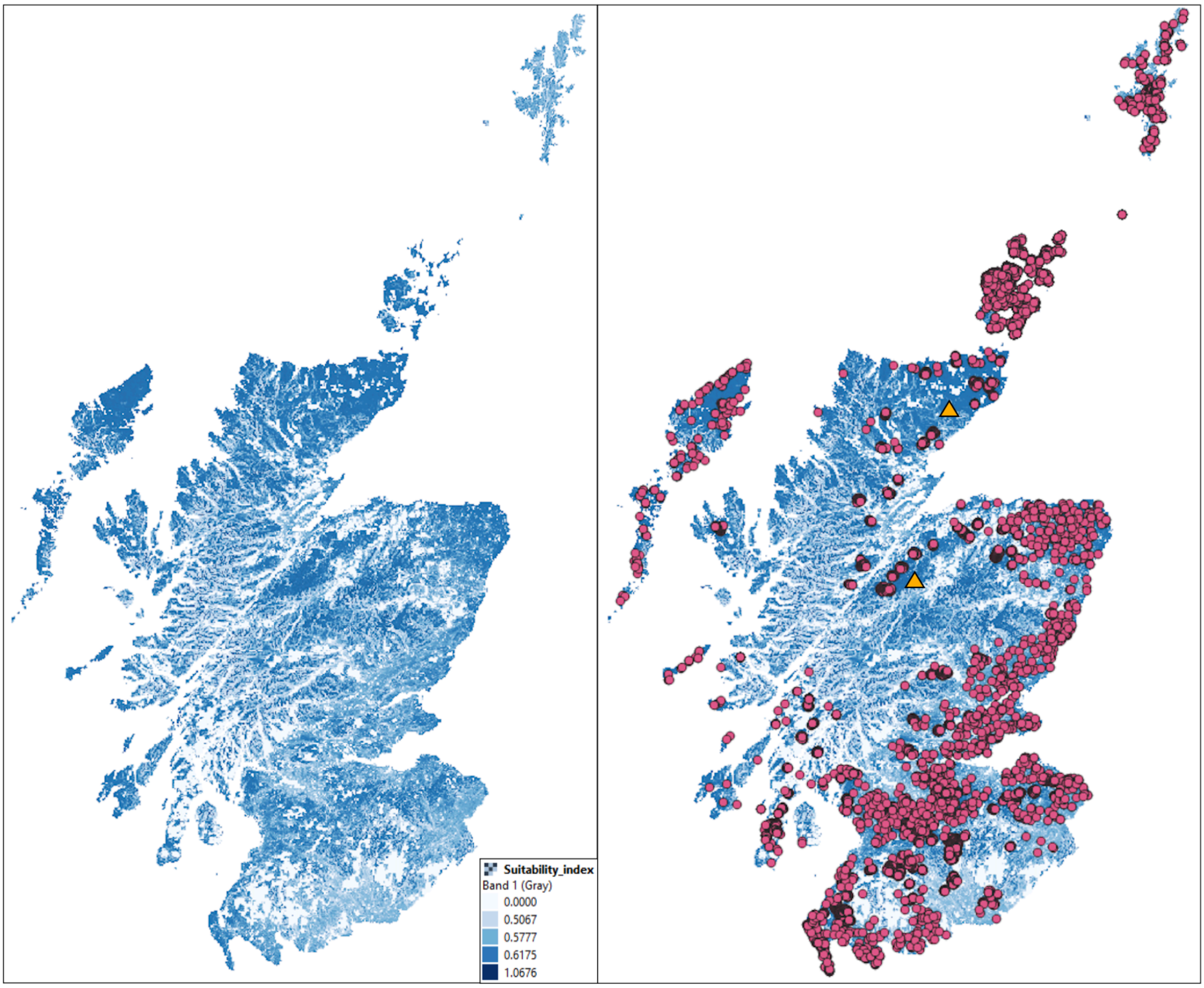


Figure 3. Suitability index (left) and suitability index overlapped with operational wind turbines (right). The orange triangles represent the proposed gap.

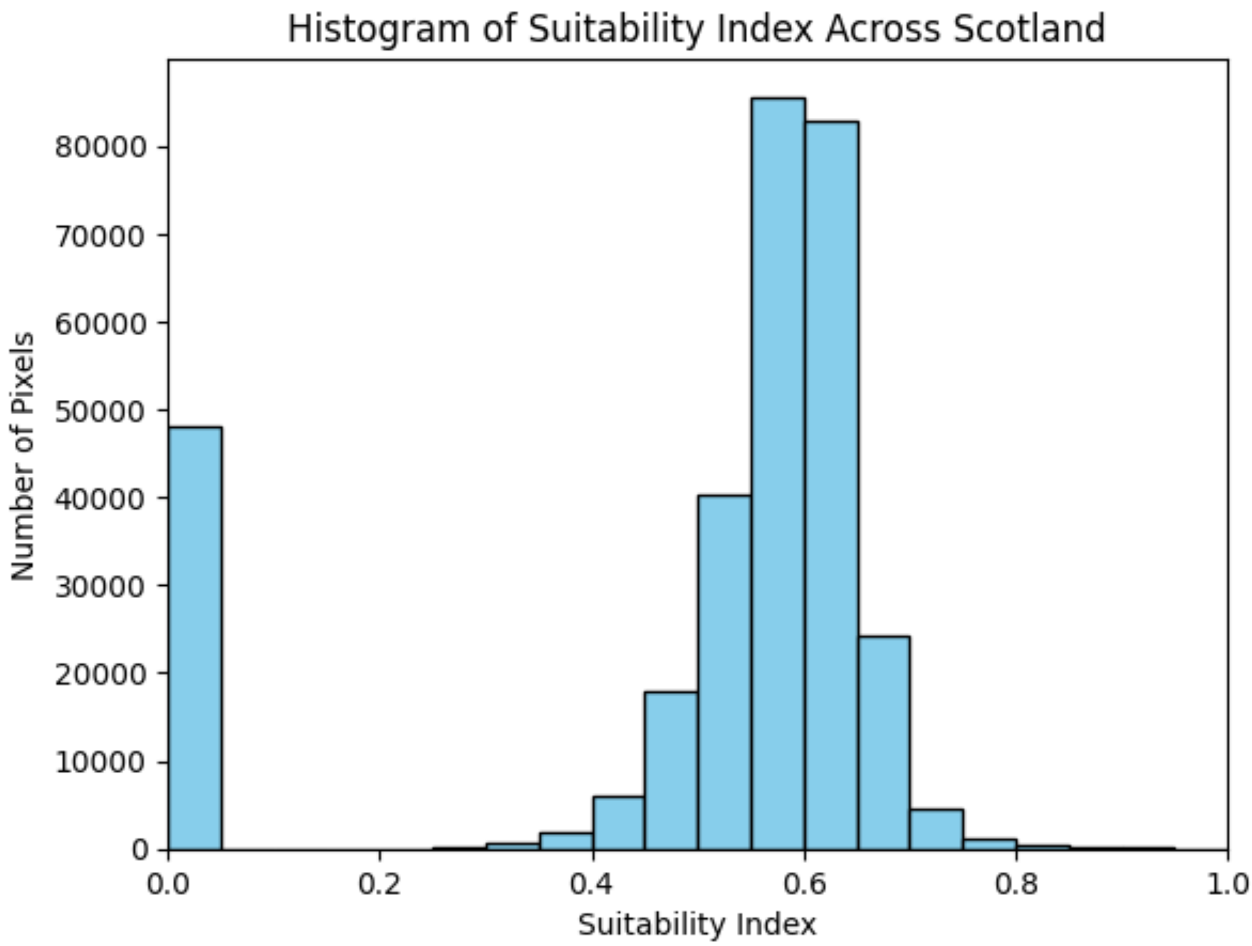


Figure 4. The overall distribution of suitability across Scotland.

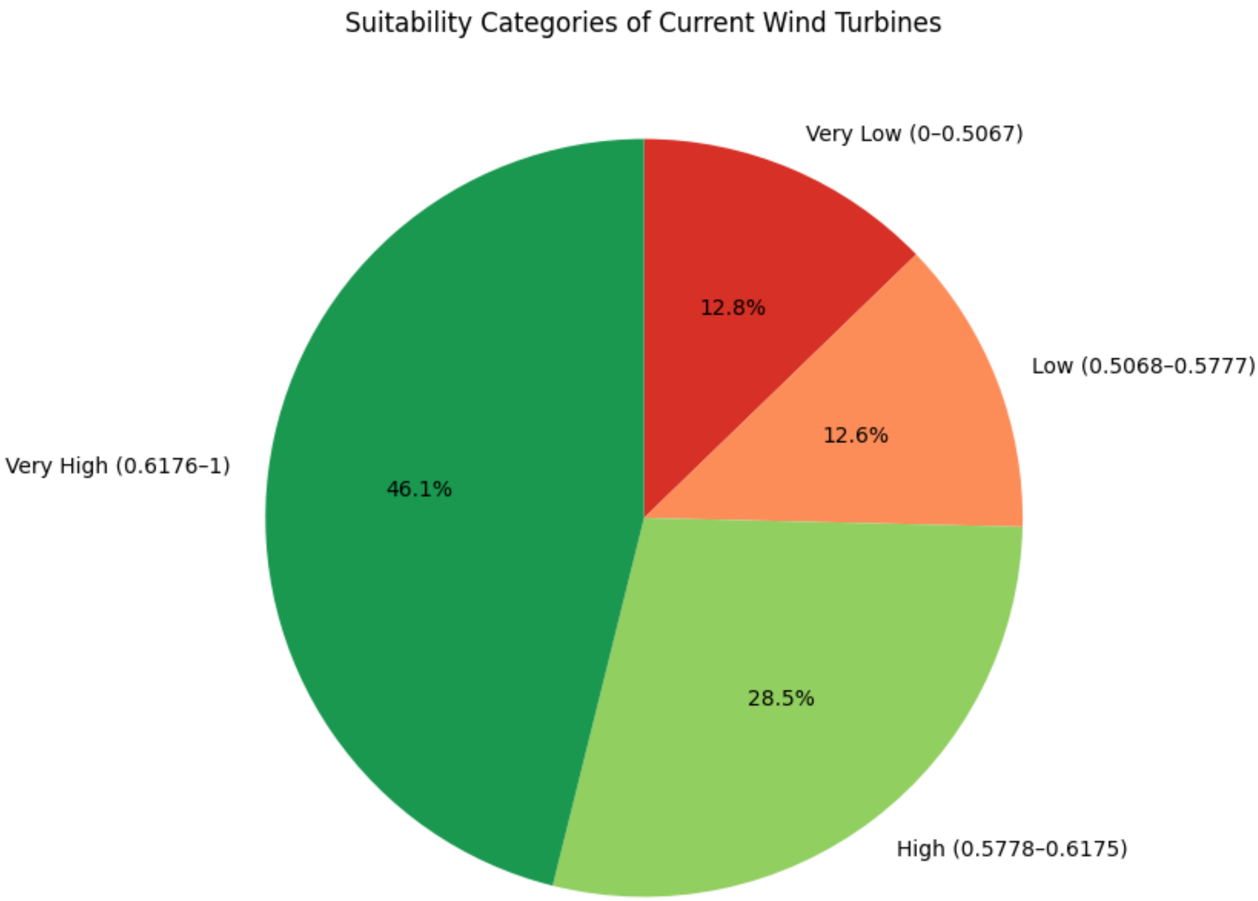


Figure 5. The proportion of current wind turbines in each suitability category.

```
# Code for generating and visualizing results
# ...
```

Discussion

The suitability index depends heavily on the contrast in the spatial distribution of wind speed and slope, given their relatively higher weights. High wind speeds were concentrated in the north-western Highlands, Argyll and Bute, and parts of the Scottish Borders, mainly due to eastward-moving Atlantic depressions that bring strong winds and clouds continuously throughout the year. However, the Highland regions are characterised by complex mountainous topography, which renders wind farm construction challenging. In contrast, the slope analysis revealed that flatter terrain is found along the east coast—including Aberdeenshire, Fife, and much of the Central Belt—as well as on the islands. These contrasting spatial patterns of the two factors result in a few regions that simultaneously possess abundant wind resources and an ideal construction environment, which explains that the suitability tends to cluster at a moderate level of 0.6, with few regions reaching a suitability greater than 0.8, as shown in Figure 4.

Nevertheless, Figure 3 (left) clearly illustrates that high-suitability areas concentrate in north-eastern and central Highland regions, eastern Aberdeenshire, the Central Belt, and parts of Dumfries & Galloway, which largely correspond to the slope criterion. Even though slope accounts for 30% of the score compared to 50% by wind speed, there is a larger variation — from 0° in low-lying areas to nearly 29° in rugged uplands — than in the annual wind speed, which ranges from 0 to 19km/h. Therefore, areas of steep terrain, such as the western Highlands and northern Argyll & Bute, are substantially less suitable. Meanwhile, the eastern coastal belt and the inland plains, which have moderate but consistent winds and extremely low slopes, are the most suitable areas for a wind farm. This is further reinforced by the well-constructed power grid and road networks near cities.

Whether the model reflects a realistic situaiton is assessed by the comparison between the suitability index and existing turbine locations. Based on Figure 3 (right), the turbines generally occupy areas with the highest suitability, such as the eastern coast and the Central Belt, though with a few exceptions. For instance, areas in Shetland are occupied with dense wind turbines despite the remoteness from the power grid. This could be explained by the evaluation considering only the above-ground high-voltage transmission network. Subsea infrastructure connecting Shetland to mainland Scotland was missing, which reduced the suitability of the remote islands (Billington, 2022). Although the proximity-to-grid criterion was deliberately assigned a lower weight due to its incomplete representation, it may still underestimate the feasibility of a wind farm on remote islands. Hence, modelling can be improved by incorporating both above-ground and subsea transmission in the future.

The pie chart in Figure 5 further provides a systematic examination of the correspondence between the model and the real world. Nearly three-quarters of current wind turbines fall into the high or very high suitability categories. This strong correspondence suggests that the selected criteria—wind speed, slope, road accessibility, and grid accessibility—are used in actual wind farm planning. Because suitability clustered within a narrow range, the quantile classification was used to ensure each category contained the same number of pixels. A limitation of this approach, however, is that the threshold between categories reflects only relative suitability within the data rather than absolute suitability in a real-world scenario. Hence, areas classified as “very high” suitability are not equivalent to optimum locations for a wind farm. In addition, we recognise that 12.8% of existing turbines are located in the very low suitability area, mostly on constrained land use. This does not necessarily indicate an error in the analysis but reflects limitations in the data and the analysis. The resolution of all raster layers is resampled to 500 m, which blurs the boundaries between adjacent land-use types. Moreover, some of the constrained land uses, such as woodland and urban areas, are not strictly prohibited from wind farm construction, as mentioned in the method section, which means some turbines take place at modified woodland and urban fringes. Hence, the constraint layer is a generalisation that shall be treated with caution.

The MCE in this study mainly focused on the quantifiable physical and infrastructural factors, while more nuanced social considerations related to wind farm implementation were overlooked. In Guan’s (2022) analysis of onshore wind farms in Germany, visual impact was considered a crucial factor, evaluated based on objective factors such as landscape sensitivity, visibility, duration, and more subjective viewers’ responses. Similarly, Scottish Natural Heritage (2017) emphasises the importance of visual assessments for mitigating social opposition. A comprehensive evaluation of wind power suitability in Scotland should therefore integrate economic, environmental, and social factors and adopt methods from quantitative and qualitative perspectives to more thoroughly address the complex problem of wind farm siting.

Overall, future planning of wind farms shall prioritise locations classified as high or very-high suitability, as these areas demonstrate strong correspondence with existing turbine implementation. The main deviation between the model and current turbine distribution occurs in parts of the northern and eastern highlands (orange triangle in Figure 3, right), where relatively sparse wind turbines are distributed across extensive high-suitability land. A detailed, high-resolution analysis of the two regions, especially of topography and interactions with surrounding woodland, is necessary.

Conclusion

This study applied multi-criteria evaluation to assess the suitability of wind farm development across Scotland, integrating key physical and infrastructural factors as well as land-use constraints. The results illustrate a clear spatial pattern where high and very-high suitability areas are concentrated in the north-eastern Highlands, eastern Aberdeenshire, the Central Belt, parts of Dumfries and Galloway, and several island regions. Comparison with existing turbine locations indicates a strong alignment, with nearly three-quarters of turbines situated in the two highest suitability classes. The correspondence shows overall success in criterion selection, but outliers, such as turbines on remote islands and constrained areas, reflect the underrepresentation of the power grid and the low resolution of the data. Finer-scale assessments and broader socio-environmental evaluations that consider visual impact are expected to improve the model.

Appendix

```
import pandas as pd
import geopandas as gpd
from shapely.geometry import Point
import matplotlib.pyplot as plt
import rasterio
import numpy as np
from google.colab import drive
drive.mount('/content/drive')
```

```
Mounted at /content/drive
```

```
#Merged vector of the constructed onshore wind turbines with the su
Comparison = gpd.read_file('/content/drive/MyDrive/GG3209 final rep
Comparison
```

显示隐藏的输出项

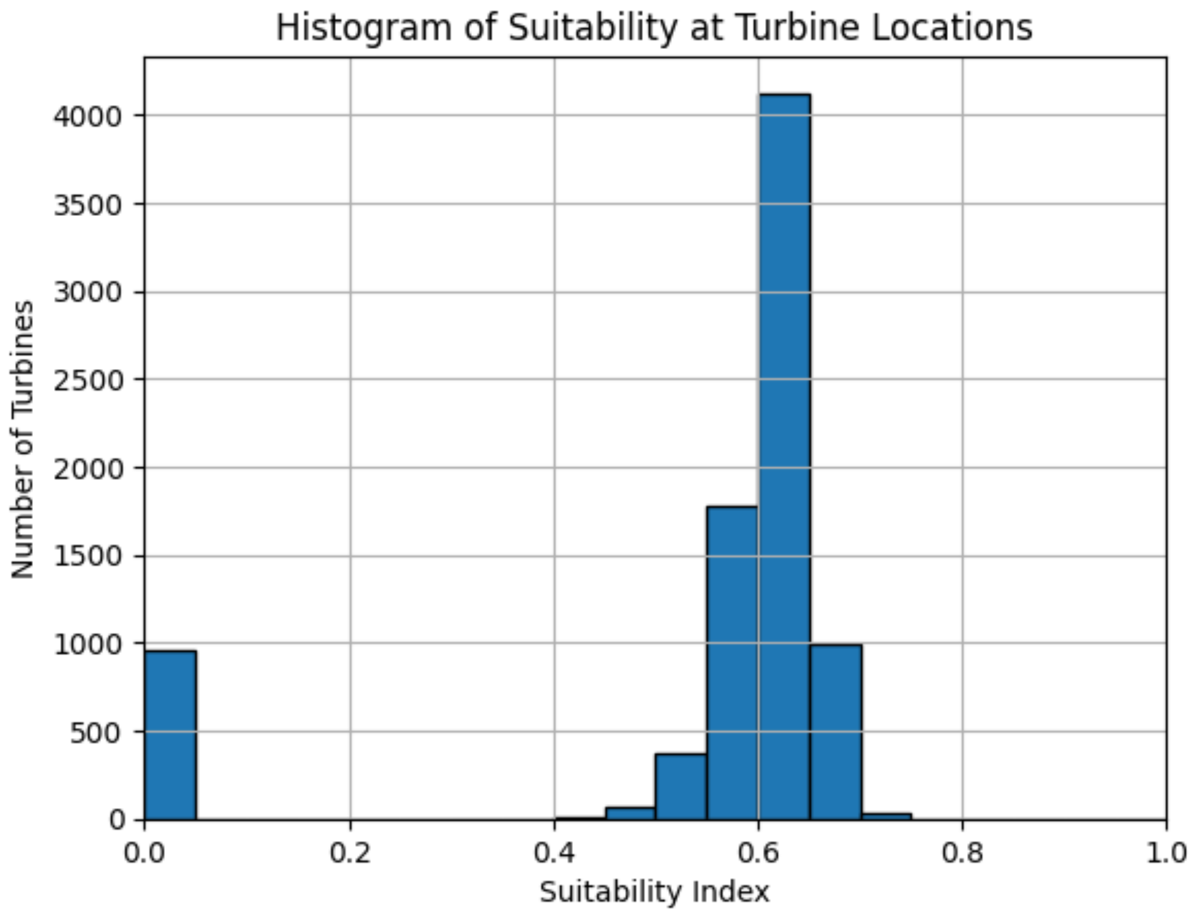
```
Comparison.rename(columns={"SAMPLE_1":"Suitability"}, inplace=True)
Comparison.head()
```

显示隐藏的输出项

```
#Histogram of Suitability at Turbine Locations
bins = np.arange(0, 1.05, 0.05)

Comparison["Suitability"].hist(bins=bins, edgecolor='black')

plt.xlabel("Suitability Index")
plt.ylabel("Number of Turbines")
plt.title("Histogram of Suitability at Turbine Locations")
plt.xlim(0, 1)
plt.show()
```



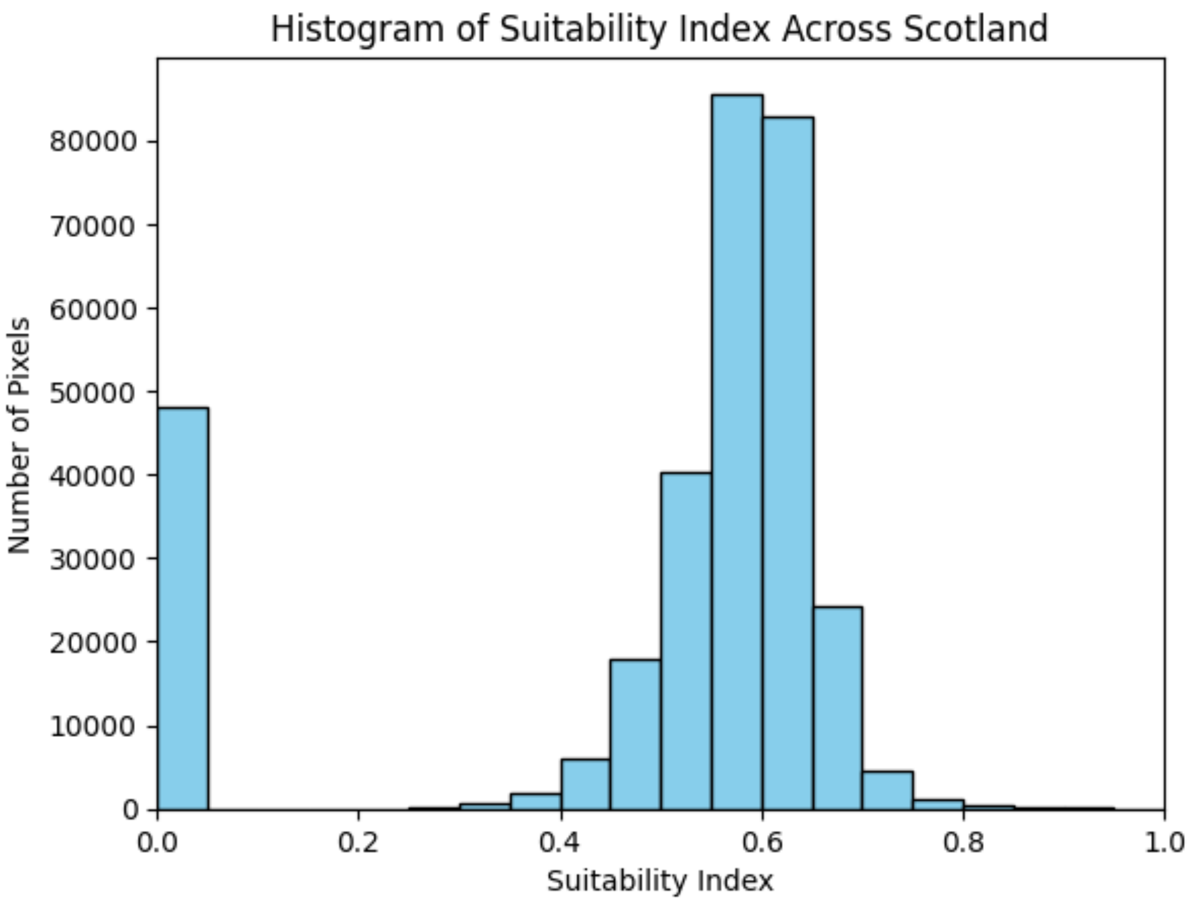
```
#Figure 4
with rasterio.open('/content/drive/MyDrive/GG3209 final report/Suit
    raster = src.read(1)
    nodata = src.nodata
    print("No-data value:", nodata)

    raster_valid = raster[raster != nodata]

bins = np.arange(0, 1.05, 0.05)

plt.hist(raster_valid.flatten(), bins=bins, color='skyblue', edgecc
plt.xlabel("Suitability Index")
plt.ylabel("Number of Pixels")
plt.title("Histogram of Suitability Index Across Scotland")
plt.xlim(0, 1)
plt.show()
```

```
No-data value: -3.4028234663852886e+38
```



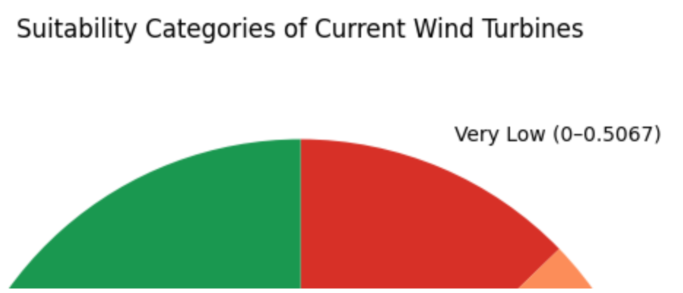
```
bins = [0, 0.5067, 0.5777, 0.6175, 1]
labels = [
    "Very Low (0–0.5067)",
    "Low (0.5068–0.5777)",
    "High (0.5778–0.6175)",
    "Very High (0.6176–1)"
]
```

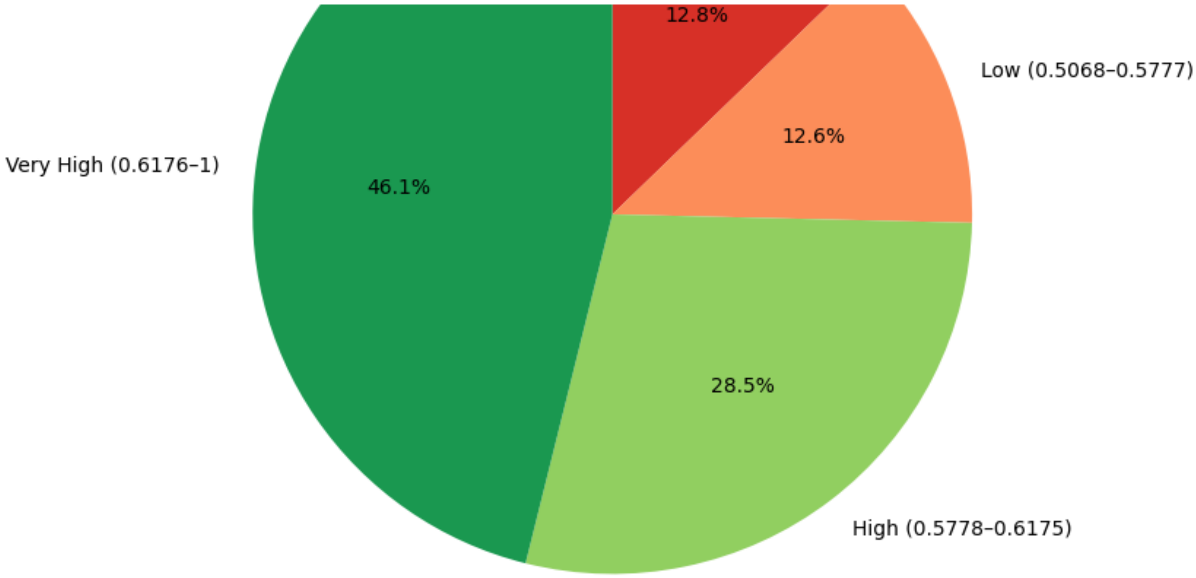
```
Comparison["Category"] = pd.cut(
    Comparison["Suitability"],
    bins=bins,
    labels=labels,
    include_lowest=True
)
```

```
counts = Comparison["Category"].value_counts().sort_index()
percentages = counts / counts.sum() * 100
```

```
colors = [
    "#d73027",
    "#fc8d59",
    "#91cf60",
    "#1a9850"
]
```

```
#Figure 5.
plt.figure(figsize=(8, 8))
plt.pie(
    percentages,
    labels=labels,
    autopct="%1.1f%%",
    startangle=90,
    counterclock=False,
    colors=colors
)
plt.title("Suitability Categories of Current Wind Turbines")
plt.show()
```




12.8%
Low (0.5068–0.5777)
12.6%
Very High (0.6176–1)
46.1%
28.5%
High (0.5778–0.6175)

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