Suitable Sites for Wind Farms in Friesland - A Case Study

Diana Radovanovici, Filip Szutowicz and Mafalda Candal

Amsterdam University College

Introduction to Geographic Information Systems

Eduardo Dias

November 22nd, 2024

Index

Introduction

A low-carbon energy supply is critical for mitigating climate change and driving the transition to sustainable energy systems. New EU targets established at the end of 2023 require at least 42.5% of European energy consumption to come from renewable sources by 2030 (Statistics Netherlands, 2024). While the implications for the Netherlands' national targets remain unclear, these ambitious goals highlight the need to explore opportunities for expansion and optimisation across all renewable energy sources.

In the realm of wind energy, the Netherlands' target of 6,000 MW of onshore wind energy by 2020 was only met by 70%, making onshore wind energy production a strong candidate for enhancement, namely by allocating more land to it. Friesland ranked as the third province with the lowest operational onshore wind capacity at the end of 2020, achieving just 37% of its goal (*Highlights Onshore Wind in the Netherlands 2014-2020*, 2021). This paper aims to conduct a preliminary assessment to identify additional areas suitable for onshore wind energy production in the province of Friesland, considering two spatial constraints—proximity to roads and Natura2000 sites—and three preference criteria—maximal distance from residential areas, preferable pasture or shrubland, and low-risk areas for birds. The study accounts for human proximity, biodiversity preservation, and practical land-use factors.

Figure 1: map showing Friesland (red) within the Netherlands and its provinces

Data

Layer	Date	Resolution	Source	Format
gadm41_NLD_1	July 2022	N/A	GADM maps	vector
Wegvakken	November 2024	N/A	Rijkswaterstaat (RWS)	vector
Natura2000	2022	N/A	Natura 2000	vector
BBG2017	2017	N/A	Netherlands Statistics Bureau	vector
NDVI	21.09.2024	10 x 10 metres	Copernicus, Sentinel-2 satellite	raster
Gevoeligheid	2021	N/A	Sovon Vogelonderzoek Nederland (Nijmegen)	vector

Table 1: data descriptions

The **GADM Database of Global Administrative Areas** is a highly detailed geographic dataset providing precise administrative boundary information for nearly all countries and territories worldwide. The database includes boundaries for multiple administrative levels (e.g., countries, states, districts), offering comprehensive and hierarchical spatial data essential for research, policy-making, and geographic analysis. The GADM Database is used in our analysis to define the administrative boundaries of Friesland for spatial analysis. We selected the latest map of the Dutch provinces provided, which was published in July 2022 and ensures accuracy and reliability, as Friesland's borders have remained unchanged since its publication.

The **National Road Database** provided by the Rijkswaterstaat (RWS) contains information about all of the road authorities in the Netherlands and includes a standardised topological map of the roads and waterways in the country. It is a reliable open datasource that belongs to the RWS, which has been in charge of the Dutch road and water system since 1798. We have decided to use the latest road system map provided, which was published on the 1st of November 2024. The data provided by the RWS will allow us to map the regions around roads where wind turbines cannot be built.

The **Natura 2000** dataset is published by the European Environment Agency (EEA) and maps protected areas in the European Union, based on the 1979 Birds Directive and the 1992 Habitats Directive. The data is provided by each EU member state, and the database is updated approximately once every year. However, the latest dataset available is the 2022, which is the one we used, as we still found it apt for our analysis. The EU Bird and Habitats Directives are legally binding and if a project does not follow the Special Protection Areas, then it can be subjected to legal scrutiny (European Union, 2009). Therefore, the Natura 2000 data will allow us to exclude the areas where wind turbines cannot be built.

The BBG2017 is provided by the **Netherlands Statistics Bureau** and describes land-use. This data is used to extract the location of residential areas and consider proximity to these regions when computing the best locations for wind turbines. This concern is raised as severe negative effects of wind turbines in human populations have been documented, decreasing well-being and diminishing social acceptance of this energy source (Krekel & Zerrahn, 2017). The latest dataset available is the 2017 one, which is still fairly suitable for our paper, as fundamental changes in the location of residential areas are unlikely to have occurred.

The satellite images in red and NIR bands, necessary to calculate the NDVI, were provided by **Copernicus**, a component of the European Union Space Programme. Those images are used to create the NDVI layer for Friesland. By means of remote sensing, NDVI is used to differentiate the areas of pasture and shrubland, most suitable for placement of wind turbines. A total of 8 images were downloaded, 4 for each band. We needed 4 images per band in order to cover the whole area of study, Friesland, because it lies on the intersection of those photos. All the images were taken on the same day, 21.09.2024.

The data about sensitivity of birds to wind turbines was taken from **Sovon Vogelonderzoek Nederland**. The sensitivity parameter is a hypothetical measurement of the risk of negatively impacting birds if wind turbines are placed at a given site. This parameter accounts for the possible mortality of the birds, but also the overall negative effect of wind turbines on the birds' habitats (Sovon Vogelonderzoek Nederland, 2021). The parameter ranges from 1 to 100, with the whole Waddenzee area set to 999 to highlight that it is impossible to place wind turbines there because of this area's importance for birds as a UNESCO Natural World Heritage site (*Wadden Sea*, n.d.).

The inclusion of the bird sensitivity in our study stems from the immense impact that wind turbines have on those organisms. They can have a detrimental influence on populations of endangered bird species (Carrete et al., 2009) and consideration of the sensitivity of bird populations can significantly limit the adverse effects (*Data Zone - BirdLife International*, 2024). Acknowledgment of the impact that projects like wind turbine construction have on bird populations becomes essential in face of the biodiversity crisis. Very recently, the first contemporary bird species Slender-billed Curlew *Numenius tenuirostris* was declared extinct in the European mainland (Buchanan et al., 2024), vividly showing the risk stemming from the negligence of bird protection.

Methodology

This preliminary assessment follows a 5-step methodology. The first step consists of defining the constraints, the following three steps define the preferences and the last step combines those elements by means of a weighted function. The first four steps are illustrated with a flowchart. The red boxes depict the input layers, while the green boxes contain the output layer of each flowchart.

Defining constraints

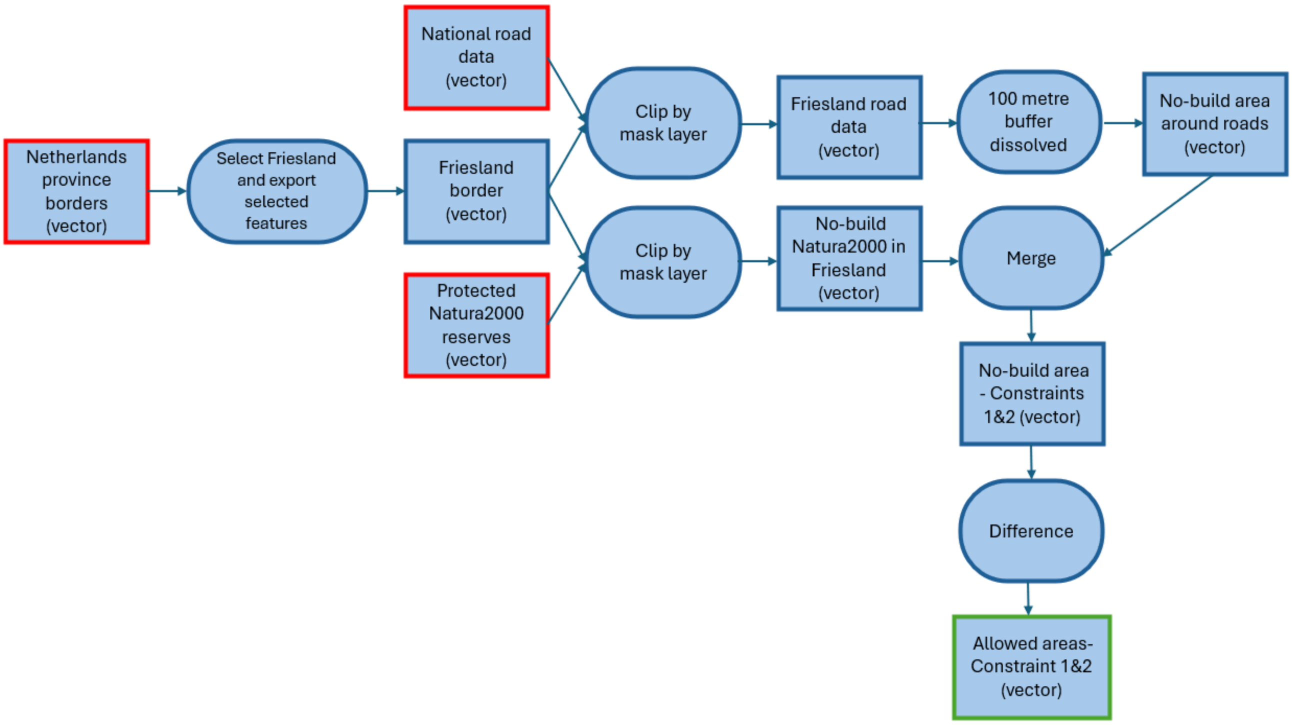

Figure 2: flowchart depicting the method for creating a vector layer with the areas in the Friesland region where building of wind turbines is allowed

The first stage of the analysis was defining allowed areas in Friesland by applying constraints based on road proximity and Natura2000 reserves. Figure 2 provides an overview of the steps followed.

Firstly, the GADM data mentioned in table 1 is downloaded and opened in QGIS 3.38.3. Then, a new layer containing the Friesland border is created by *attribute selection* in the gadm41_NLD_1 layer that contains the provinces in the Netherlands. The National Road data is *clipped* to the Friesland border to obtain the Friesland road data to which a *100-metre buffer* is applied, to create a No-build area around roads dataset (Dutch National Legislation).

Using a similar process, the downloaded Natura 2000 data presented in Table 1 is *clipped* using the Friesland border as a mask layer to obtain a No-build area around protected zones. To obtain a map with the spatial and environmental restrictions, the No-build layer around protected zones is *merged* with the No-build layer around roads to create a No-build areas map. However, we are interested in where wind turbines can be built, so the *difference tool* is used on the No-build areas layer to create our Allowed areas map.

<u>Defining preference 1</u>

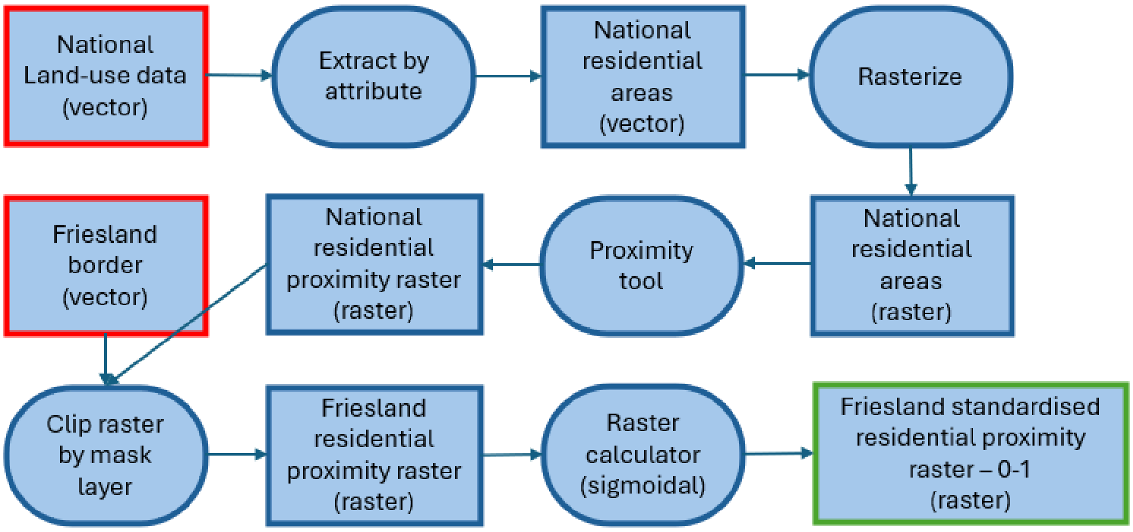

Figure 3: flowchart depicting the method used to create a standardised residential proximity layer for the Friesland region

The second stage of the analysis involved creating a standardised residential proximity raster. This was necessary to concretely represent preference 1: maximal distance from residential areas. Figure 3 provides an overview of the steps taken to standardise this measure.

We begin by using the *extract by attribute* tool on the BBG2017 dataset, the selection attribute being *Omschrijvi*, and the value representing residential areas being *Woongebied*. Then, because we want to perform a proximity analysis, it is required to *rasterize* the new vector layer containing national residential areas. The *proximity* tool is used on the national residential areas raster to obtain a national residential proximity raster. Only at this stage can the Friesland border be used as a *mask layer to clip* the residential areas, as it is fundamental that the proximity map includes residential areas outside of Friesland too. This way we consider all houses that would be close to the wind turbines, including those that would be just outside the border of our desired province. But now, we can *clip* the proximity map and then use the *raster calculator* to standardise the distances obtained in Friesland. We chose to standardise the distance from residential areas by use of a sigmoidal function, because this function better models varying rates of change in suitability across distances, and also allows to highlight specific thresholds.

A sigmoidal function has the following standard format:

$$f(x) = \frac{1}{1+e^{-k(x-\frac{n}{2})}},\ 0 < x < n \text{ and } f(x) = 1,\ x \geq n$$

where n is the approximate distance in kilometres over which the nuisance caused by wind turbines has an effect, and k is a shape parameter that controls the steepness of the curve - higher k makes the curve steeper, meaning the change from low to high preference happens more abruptly around the midpoint (n/2).

We chose the parameters k and n to fit the information published by the **NLVOW (Dutch Association for Residents Near Wind Turbines)**. Founded in 2013, it is a legitimate advocacy organisation that constructively represents residents' interests in energy transition projects, making transparent, fact-based contributions. Because residents were the utmost priority, we considered the voice of this association would be the best source. While 1km is the minimum distance to reduce noise disturbances and other nuisances, 2km - 2.5km is the range put forward to address broader considerations such as health, well-being, and property value impacts, based on international examples from countries like Denmark, Bavaria, and Poland (*A Clear Distance Standard Is Safe*, 2022). We chose 1km and 1.5km to be our 1st and 3rd quartile thresholds respectively, and anything above 2km is considered nearly ideal. The final expression is depicted below.

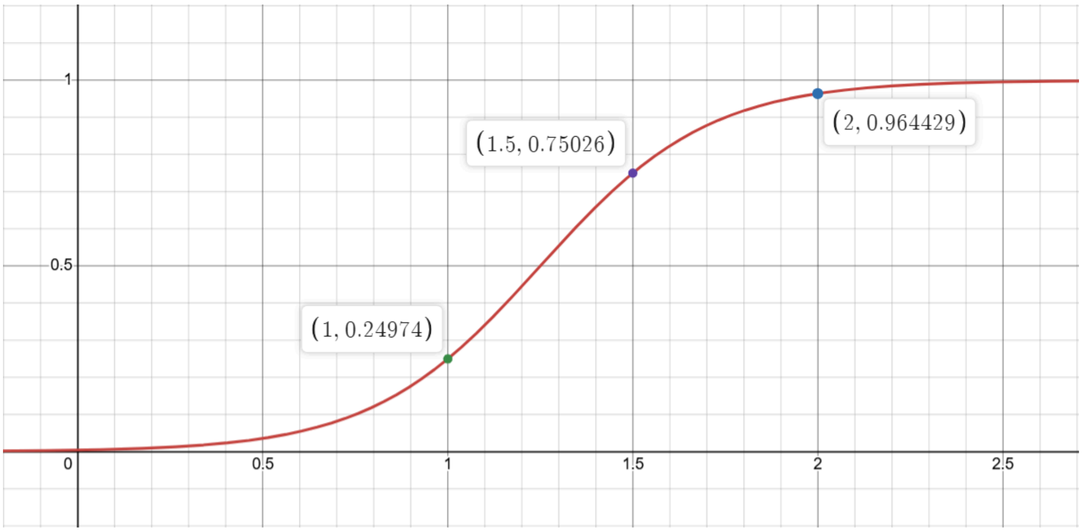

Figure 4: graphing of expression $f(x) = \frac{1}{1+e^{-4.4(x-1.25)}},\ x > 0$ (Desmos Graphing Calculator, 2024)

By applying this function, we obtain a 0 to 1 value map depicting the impact that wind turbines have on the residents based on proximity, values closer to 0 meaning severe negative impact and values around 1 meaning close to no impact.

<u>Defining preference 2</u>

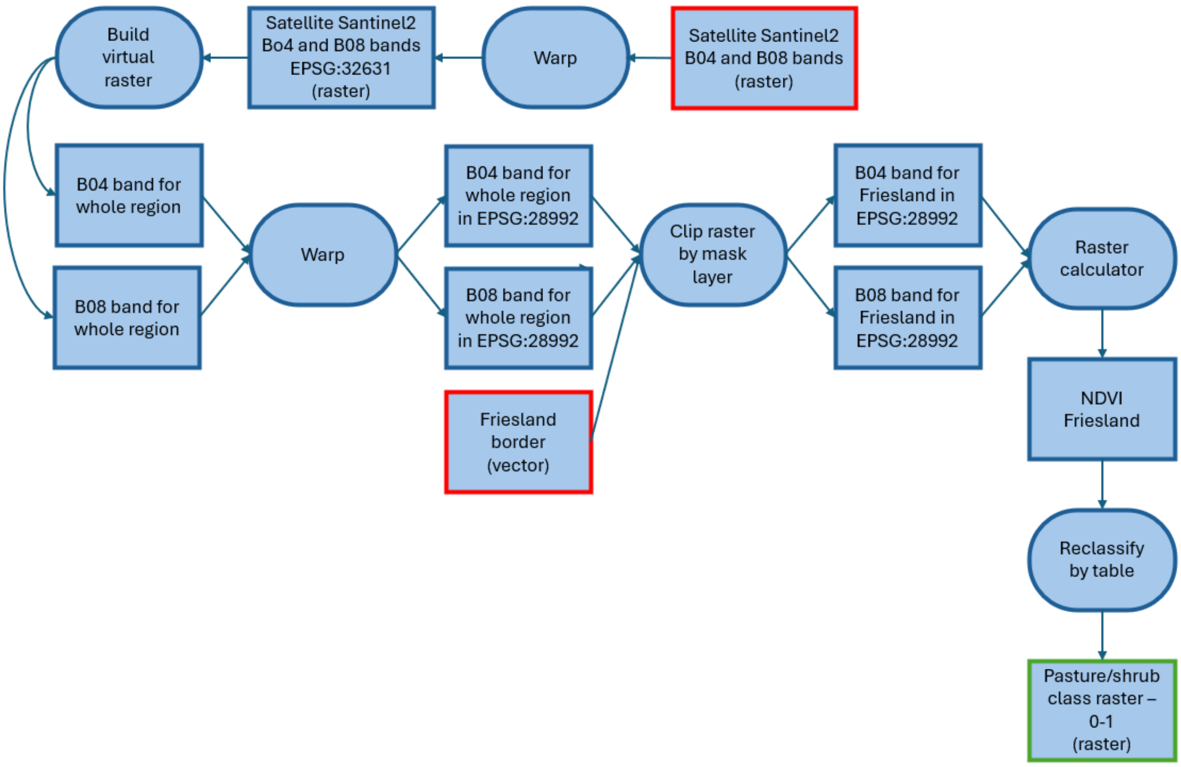

Figure 5: flowchart depicting the method used to create a standardised pasture/shrub/agro class layer for the Friesland region

The third stage is to classify the land into two classes based on NDVI. One of the classes contains the suitable sites for the placement of the wind turbines—arable land, pastures and shrubs. The other class contains the remaining unsuitable sites—forests, built-up areas, bodies of water.

From the Copernicus database download images (raster files) taken by Sentinel-2. For the NDVI analysis we are interested in bands 4 (red) and 8 (NIR). The images we used were taken on 21.09.2024. This date, being in late summer, is not ideal for the data used in an NDVI analysis, because the plants start changing colours around this time. However, the cloud cover on this day was particularly low, which is beneficial for such a study. Also, pastures being the most significant area of our interest, largely retain their summer colours at this time, allowing us to detect them.

The area of study, Friesland, lies on the intersection of 4 images from Sentinel-2. Firstly, we have to reproject one of them (originally it was in EPSG:32632) using the *warp* tool from EPSG:32632 to EPSG:32631, so that it has the same coordinate reference system (CRS) as the other raster layers for the NDVI calculation. Then we have to combine them using the *build virtual raster* tool. Only then we reproject the result of that operation to the project CRS being EPSG:28992. We avoid reprojecting each individual raster file to the target CRS before merging, as the reprojection process can create no-data margins along the edges of the layers. These margins would complicate the merging process, because they could create no-data areas in our interest area. By adjusting the order of reprojections, we effectively eliminate this issue. After that, we clip the two layers to the land borders of Friesland using *clip raster by mask layer.* Once we receive the clipped layer covering the entire land surface of Friesland for each of the two bands, we proceed to the NDVI calculation itself.

Using the raster calculator we implement the formula for NDVI and create the layer with NDVI values for Friesland. Then, we reclassify this layer based on the NDVI values into two classes mentioned above using the *reclassify by table* tool. Literature suggested the range of NDVI values 0.2 - 0.5 for pastures, shrubs and arable land (‘suitable’ class), the rest being classified as unsuitable (Akbar et al., 2019; Brown, 2018). However, iteratively adjusting those ranges to best fit our data, we obtained a significantly different range. It is -1 to 0.45 for the ‘unsuitable’ class, and 0.45 to 1 for the ‘suitable’ class. The accuracy of the NDVI classification into the two land use classes was assessed relative to the PDOK satellite image. The accuracy calculated with the *AcATaMa* plugin is 0.75879, with standard error of 0.03. This is a satisfying accuracy, allowing for the use of this classification in the study.

	Validation				
	1 (water,builtup,forest)	2 (field,pasture,shrub)	Total	User's accuracy	Total class area (km²)
1	38	31	69	0.55072	1389.05
2	12	97	109	0.88991	2204.28
total	50	128	178		3593.33
Producer's accuracy	0.75917	0.75864		0.75879	

Table 2: Confusion matrix for the NDVI classification

At last, we applied the *neighbours* tool with *mode* operation and the neighbourhood size 5 to remove noise from the data. Thus, we obtained the layer with two land use classes: 'suitable' and 'unsuitable', with removed noise.

<u>Defining preference 3</u>

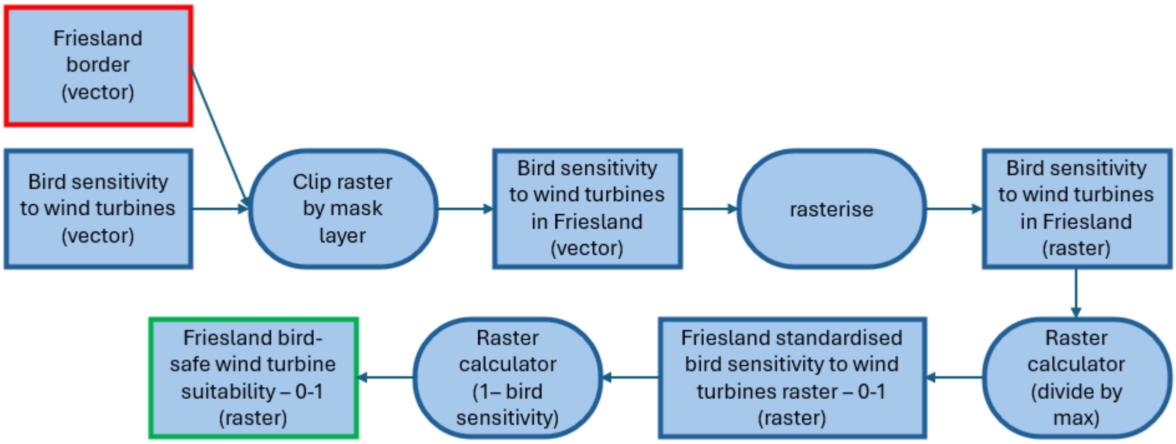

Figure 6: flowchart depicting the method to compute the standardised bird sensitivity to wind turbines in Friesland

The fourth stage is to consider what are the areas of Friesland where birds would not be heavily impacted by wind turbines. Figure 6 provides an overview of the steps followed.

First, we *clip* the Bird Sensitivity to Wind Turbines data to the Friesland Border, and then rasterize the result. Because the initial dataset measures how sensitive each area is, we standardised the raster data by dividing by the maximum value and then computed (1 - "Friesland standardised bird sensitivity to wind turbines raster") to invert the scale and attribute the higher suitability scores to the areas with the least sensitivity. The final dataset contains bird-safe zones to place wind turbines with values in a range of (0-1).

<u>Computing suitability score</u>

Finally, we use the following formula to compute our suitability scores, based on the the three ranked criteria (C1, C2 and C3):

$$min((C1 * w1 + C2 * w2 + C3 * w3), C1) * Constraints$$

where *C1* is the Friesland Standardised Residential Proximity raster, *C2* is the Standardised Pasture and Shrubs raster, *C3* is the Standardised Bird-Safe to Wind Turbines raster, and the Constraints variable is the Allowed Areas dataset computed in the beginning and rasterized.

The preferences were communicated in order according to importance and therefore a method of weighting the criteria by ranks was adequate: **Rank Sum** (good for evenly spaced priorities), **Reciprocal Rank** (suitable for top-heavy priority distributions) or **Rank Exponent** (ideal for variable priority differences that require more precise weighting adjustments). While we wanted to emphasise the first criteria (distance from residential areas), we considered that using a rank sum would offer a balanced approach which we could complement by using the minimum operator to create a soft constraint min(average suitability, standardised residential proximity). This way, it was certain that a location close to residential areas would always score lowly on the overall suitability without the need to exacerbate the difference in importance between the three criteria.

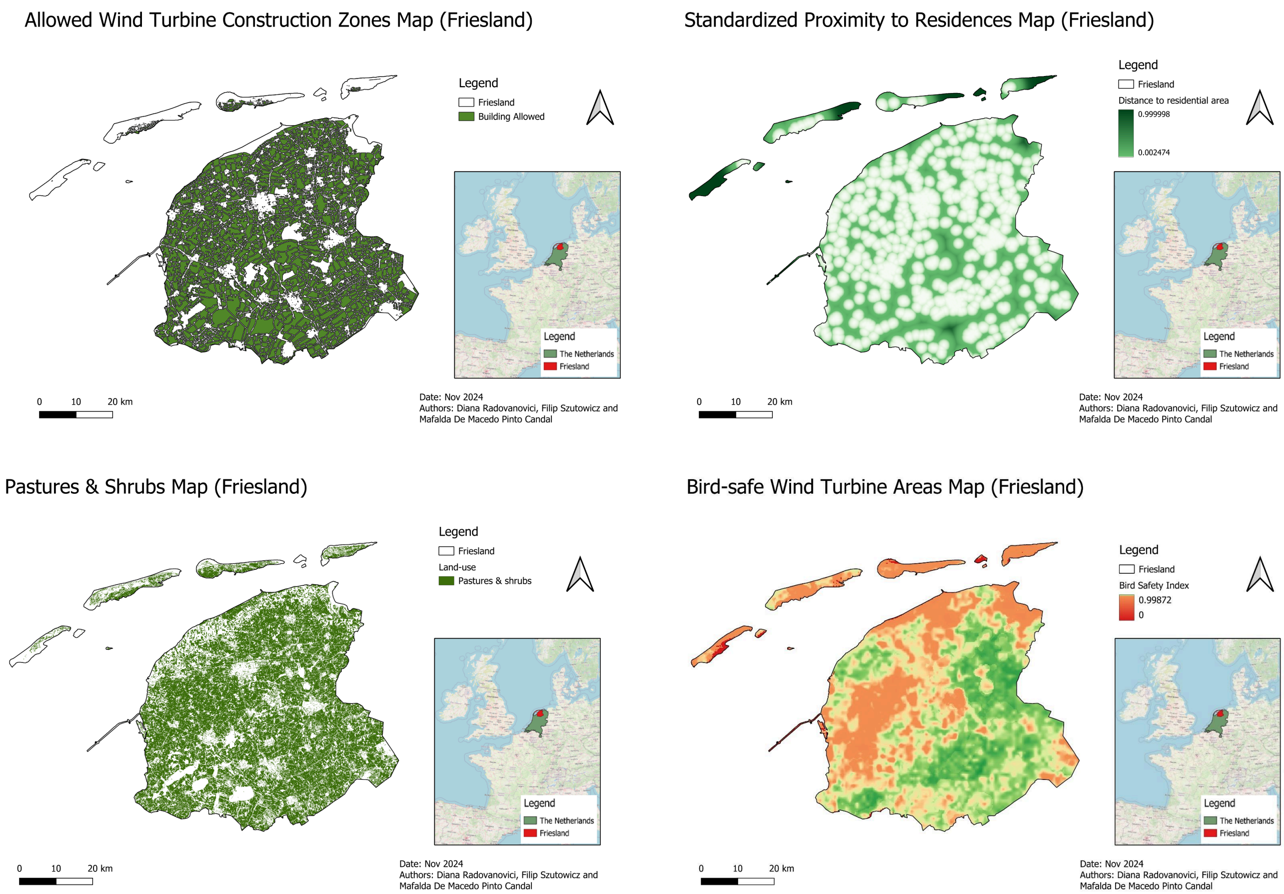

Figure 7: Visualisations of the constraints and the four criteria

Results

The final formula that was presented in the Methods section allows for the creation of a preliminary map with potential sites for expansion of onshore wind energy production in the province of Friesland.

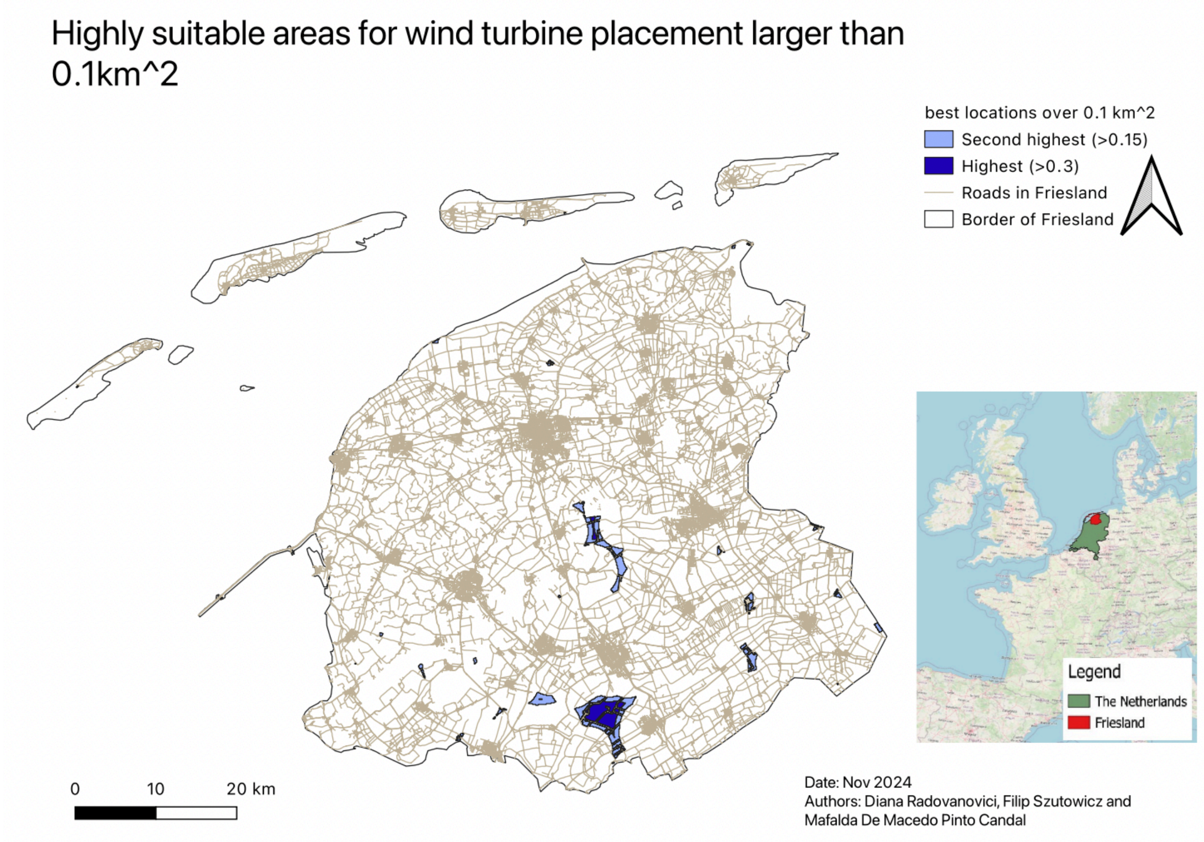

Figure 7: Two classes of areas with highest scores, with areas over 0.1 km^2.

Figure 7 showcases the best areas for building wind turbines, based on the suitability scores presented in the Methods section. Only plots of more than 25 acres (rounded to 0.1 km^2) have been taken into consideration, as that is considered to be the minimum area required for installing and maintaining a wind turbine (Benn, 2023). The suitability scores are in the range of (0 - 0.762), and we chose a threshold of 0.3 to show the best of them. As aforementioned, some of these areas are as small as 25 acres and none are bigger than 5,04 km^2, so we opted for creating a “second best areas” category to allow for an understanding of if/where bigger projects, like wind farms, could be placed. The second best have scores between 0.15 and 0.3. In total, there are 10.20 km^2 of spots with the highest suitability scores, and 29.97 km^2 of spots in the second category, a total of 40.17 km^2 areas being in the most suitable classes.

Scenario Analysis

The criteria ranking is highly dependent on the current priorities of the government. Yet, the proposed analysis holds for various rankings requested by the authorities, and in this section we will showcase that by exploring a few different scenarios. In the analysis done in previous sections we accentuated the importance of not having wind turbines near residents by using the *min* function between the weighted preference score and the residence proximity score. For the following scenario analysis, we will use the following simplified formula: $(C1 * 0.5 + C2 * 0.333 + C3 * 0.167) * Constraints$.

For a control measurement, we calculated the suitability parameter with this equation with an unchanged ranking of the parameters. The result is shown in Figure 8.

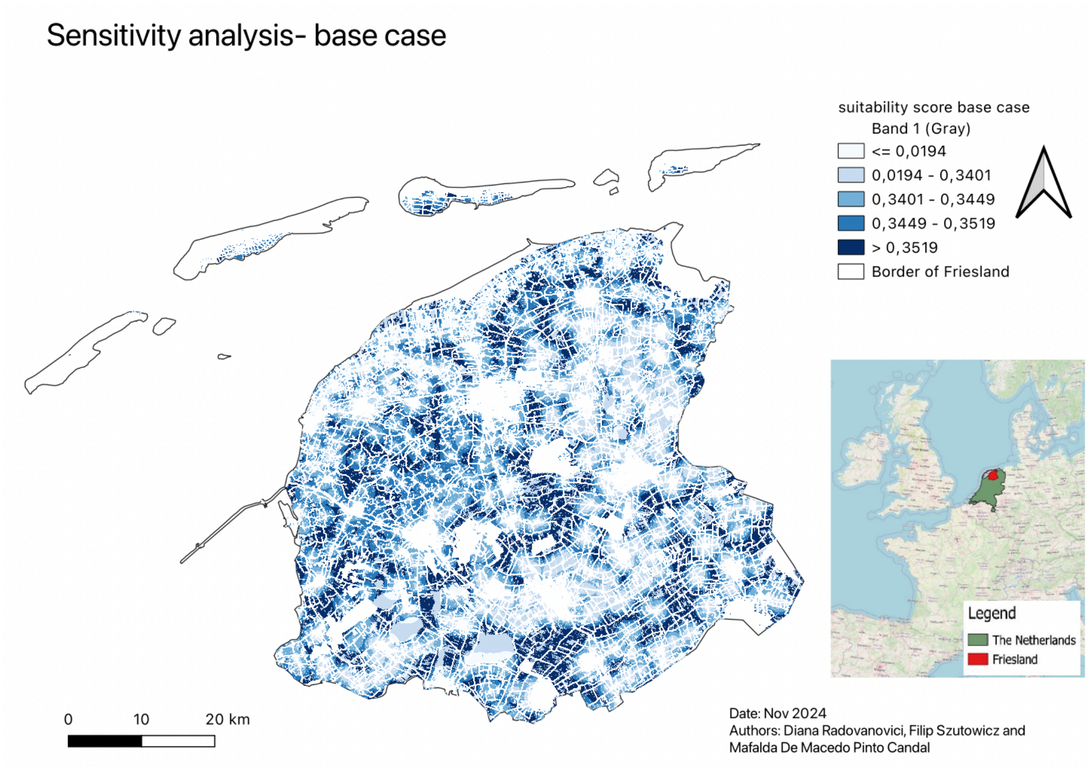

Figure 8: Base case for the sensitivity analysis- ranking of the parameters the same as in the main part of the study.

For the first case of sensitivity analysis let us consider the following scenario. If the state wants to avoid the disturbance of forests and non-pasture/shrub areas the most, then the suitable land use criterion will have rank 1. The outcome of those conditions is presented in Figure 9.

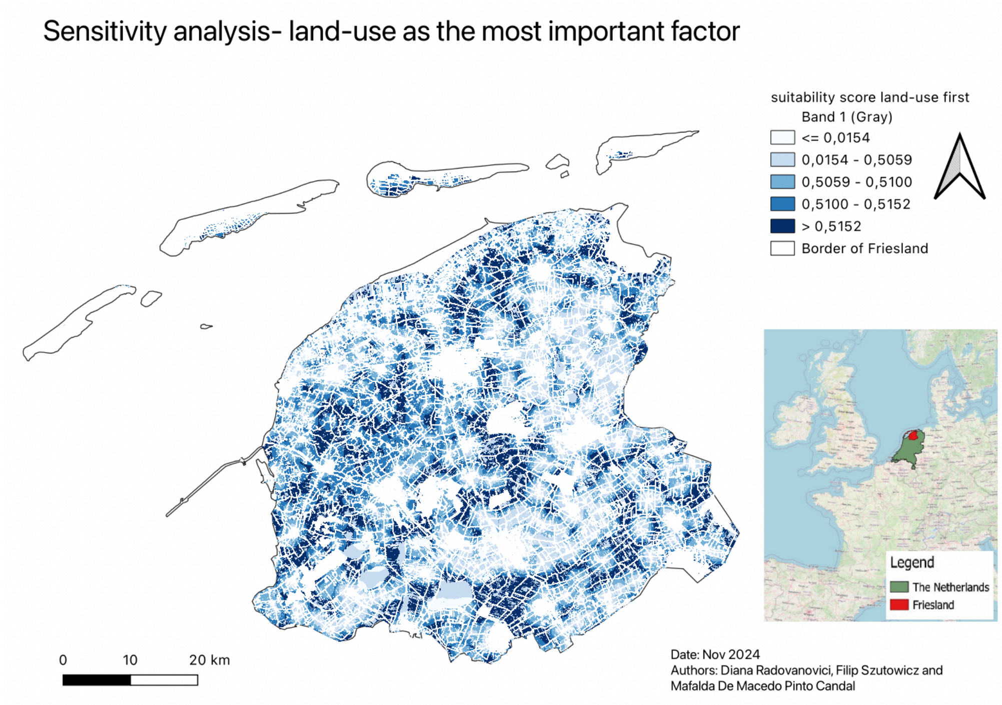

Figure 9: First case for the sensitivity analysis- Land-use as the most important factor, the ranking of the two remaining criteria preserved.

Secondly, if the state wants to put an accent on biodiversity conservation, then the bird sensitivity criterion could be ranked first in terms of importance. The resulting suitability score in this scenario is presented in Figure 10.

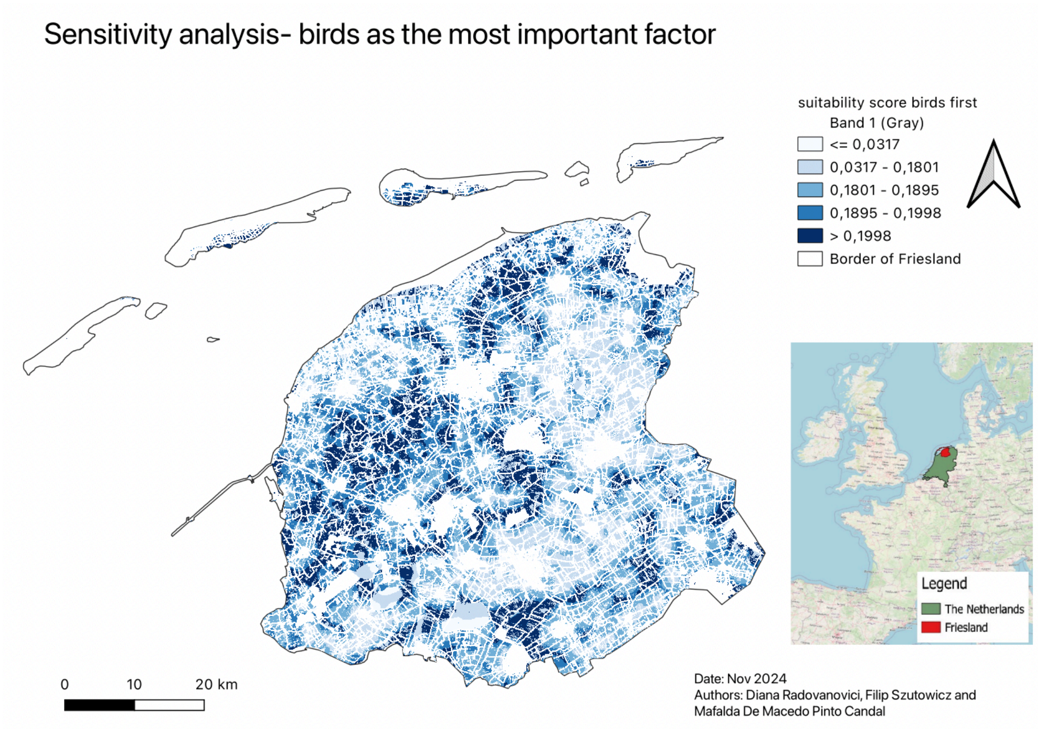

Figure 10: Second case for the sensitivity analysis- Bird sensitivity as the most important factor, the ranking of the two remaining criteria preserved.

Discussion

Strengths and Limitations of the MCA Methodology

Previous research on wind turbines has been conducted using multi-criteria analysis (MCA). Particularly, the study conducted by Hansen (2005) was dedicated to the development of a GIS-based multi-criteria analysis (MCA) methodology, incorporating fuzzy logic, to specifically address the challenges of wind farm spatial planning. This paper introduces a comprehensive theoretical background and defence for the effectiveness of this methodology in identifying suitable sites for wind farms, focusing on three main strengths: (1) effectively handling the integration of diverse data types and uncertainty, inherent to the environmental decision-making; (2) its combination with fuzzy logic provides flexibility in handling trade-offs, offering a more nuanced and robust alternative to traditional Boolean logic; (3) allowing for the weighting of criteria, enabling scenario-building and accommodating various stakeholder perspectives, which is crucial in balancing social, environmental, and economic factors. These potentialities were used in our methodology when we attributed weights to the preferences that represented the hierarchical priority between them, or implemented the soft constraint related to proximity to residential areas, contributing for a more robust, accurate and informative result.

Considerations on sensitivity analysis

The sensitivity analysis showed a relative robustness of the results of our study. For the studied permutations of ranks of criteria, little variation was visible in the spatial distribution of the resulting suitability score.

The sensitivity analysis was performed on a simplified formula for the suitability score, as it did not feature the minimum function between the weighted sum and the proximity to residential areas. That was done to make the interpretation of the results of this analysis simpler. However, it is reasonable to assume that if the sensitivity analysis was performed with the original function, the variability could be only lower than in the case of the simplified function. That is provided that proximity to residential areas remains the parameter to which the weighted sum is compared by the minimum function. In such a case, the minimum function would mean that if the proximity to residents parameter is very low, the result is likely identical across the sensitivity analysis. In other cases, the result would vary in the same manner as we studied in the sensitivity analysis.

Nevertheless, it is important to remember that it was a preliminary study and that this suitability score is inherently connected to the criteria from which it was derived. While the two constraints and three preference criteria successfully account for human proximity, biodiversity preservation, and practical land-use factors, these had to be selected from a much broader array of factors that in the real world influence and are influenced by the placement of wind turbines. The selection of the factors to be included in this study, however supported by literature, was to some extent subjective. Various stakeholders might consider very different features significant. The purpose of the sensitivity analysis was to try to account for that. However, it would be impossible to account for the full range of possible preferences. Hence, this analysis will not be suitable for all situations.

Other Limitations and Recommendations for Future Research

This section analyses some of the limitations present in this study. Firstly, croplands have a very low NDVI and affect the accuracy of the NDVI analysis. This project used images from the end of September, so a potential solution is using satellite images from the summer months, before the crops were harvested to avoid miscategorizing these areas. Moreover, bird sensitivity and Natura 2000 protected areas might be spatially correlated.

Because the Natura 2000 regions are a constraint, the Bird sensitivity to wind turbines index does not contribute as much as might be expected to the decision where not to put wind turbines. However, this criterion accounts for the fact that bird ranges are more continuous than the boundaries of protected areas, and thus usually go beyond them. Future studies can attempt to control better the correlation between these two aspects. Another limitation is that the data on residential areas is from 2017, and changes in land use might have occurred since then. Papers building upon this study are advised to look for more recent data on the distribution of residential areas. Finally, the weights could have been selected through a more complex method that better modelled the importance of the criteria. Also, a full sensitivity analysis can be done by future research, to find a better configuration on weight values.

Conclusion

Ultimately, we are confident that the multi-criteria suitability analysis performed using QGIS does accurately represent the preference and criteria communicated. It outputs a suitability raster for the province of Friesland that provides guidance in choosing the best site for construction of wind turbines, possibly helping in achieving the onshore wind energy production goals of the province of Friesland.

References

A clear distance standard is safe. (2022, April 29). NLVOW. https://nlvow.nl/clear-distance-standard-safe

Akbar, T. A., Hassan, Q. K., Ishaq, S., Batool, M., Butt, H. J., & Jabbar, H. (2019). Investigative Spatial Distribution and Modelling of Existing and Future Urban Land Changes and Its Impact on Urbanization and Economy. *Remote Sensing*, *11*(2), 105. https://doi.org/10.3390/rs11020105

Benn, T. (2023, September 18). *Land Required for a Wind Farm - What Landowners Should Know*. Lumify Energy. https://lumifyenergy.com/blog/land-required-for-a-wind-farm/

Brown, J. (2018, November 27). *NDVI, the Foundation for Remote Sensing Phenology | U.S. Geological Survey*. Www.usgs.gov. https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology

Buchanan, G. M., Chapple, B., Berryman, A. J., Crockford, N., Jansen, J. J. F. J., & Bond, A. L. (2024, November 18). *Global extinction of Slender-billed Curlew (Numenius tenuirostris)*. https://www.researchgate.net/profile/Justin-Jansen-4/publication/385906029_Global_extinction_of_Slender-billed_Curlew_Numenius_tenuirostris/links/673b3223b94c451c116031c3/Global-extinction-of-Slender-billed-Curlew-Numenius-tenuirostris.pdf

Carrete, M., Sánchez-Zapata, J. A., Benítez, J. R., Lobón, M., & Donázar, J. A. (2009). Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. *Biological Conservation*, *142*(12), 2954–2961. https://doi.org/10.1016/j.biocon.2009.07.027

Data Zone - BirdLife International. (2024). Birdlife.org. https://datazone.birdlife.org/wind-turbines-can-cause-significant-deaths-in-bird-species

Desmos Graphing Calculator. (2024). Desmos. https://www.desmos.com/calculator

Hansen, H. S. (2005). GIS-based Multi-Criteria Analysis of Wind Farm Development. *ScanGIS 2005: Proceedings of the 10th Scandinavian Research Conference on Geographical Information Science*, 75–87.

Highlights onshore wind in the Netherlands 2014-2020. (2021, July 15). Windpowernl. https://windpowernl.com/2021/07/15/highlights-onshore-wind-in-the-netherlands-2014-2020/

Krekel, C., & Zerrahn, A. (2017). Does the presence of wind turbines have negative externalities for people in their surroundings? Evidence from well-being data. *Journal of Environmental Economics and Management*, *82*, 221–238. https://doi.org/10.1016/j.jeem.2016.11.009

Sovon Vogelonderzoek Nederland. (2021). *Achtergronddocument windenergie gevoeligheidskaart vogels | Sovon Vogelonderzoek*. Sovon.nl. https://stats.sovon.nl/pub/publicatie/18101

Statistics Netherlands. (2024, June 7). *Energy from renewable sources rises to 17 percent*. Statistics Netherlands; Centraal Bureau voor de Statistiek. https://www.cbs.nl/en-gb/news/2024/23/energy-from-renewable-sources-rises-to-17-percent

Wadden Sea. (n.d.). UNESCO World Heritage Centre. https://whc.unesco.org/en/list/1314/

Declarations

All the authors equally participated in the steps.