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HORIZON EUROPE PROGRAMME – TOPIC HORIZON-CL5-2021-D3-03-05
Wind energy in the natural and social environment
Research and Innovation action (RIA)

WIMBY

Wind in My Backyard: Using holistic modelling tools to advance social awareness and engagement on large wind power installations in the EU

Grant Agreement No. 101083460
Starting date: 1st January 2023 – Duration: 36 months

Deliverable D1.4
Land & Sea use and change maps (b)

DOCUMENT INFORMATION

Deliverable number	D1.4
Deliverable title	Land & Sea Use & Change (18 months report)
Work Package	WP1
Deliverable type[1]	R - Report
Dissemination level[2]	Public
Due date	30.06.2024 (Month 18)
Pages	28
Document version[3]	3.0
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1 Type: ORDP: Open Research Data Pilot; R: Report; D: Demonstrator
2 Dissemination level: C: Confidential; P: Public
3 First digit: 0: draft; 1: peer review; 2: peer review 3: coordinator approval; 4: final version

DOCUMENT CHANGE HISTORY

Version	Date	Author	Description
DRAFT			
0.1	28.05.2024	Christian Mikovits, University of Natural Resources and Life Science (BOKU)	Creation
0.2	30.05.2024	Thomas Öberseder, University of Natural Resources and Life Science (BOKU)	Consolidation of input from contributors
FIRST PEER REVIEW			
1.0	18.06.2024	Maeva Lavigne Philippot, VUB Alena Lohrmann, Chen Ruihong, ETH Zürich	Proofreading and peer review
1.1	24.06.2024	Christian Mikovits, University of Natural Resources and Life Science (BOKU)	Consolidation of input from reviewers
COORDINATOR APPROVAL			
2.0	24.06.2024	Luis Ramirez Camargo (UU)	Scientific Coordinator review
2.1	25.06.2024	Christian Mikovits, University of Natural Resources and Life Science (BOKU)	Consolidation of input from coordinator
2.2	27.06.2024	Luis Ramirez Camargo, (UU)	Scientific Coordinator approval
FINAL VERSION			
3.0	29.06.2024	Stella Arapoglou (VUB)	Format review, version ready for submission

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SHORT ABSTRACT FOR DISSEMINATION PURPOSES

Abstract

The second version of the "Land & Sea Use and Change Maps" report, builds upon the first report D1.3. This version of the report includes several key updates, including an extended data coverage to encompass additional EU countries, enhanced change detection algorithms, and advanced statistical analyses that integrate dynamic buffer sizes and terrain data. Key updates involve refined geostatistical techniques, dynamic buffer size calculations, and integration of comprehensive terrain and biogeographical datasets. Offshore wind farm impacts are evaluated using empirical data and literature due to satellite imagery limitations. Challenges such as data accuracy from OpenStreetMap (OSM) and spatial inconsistencies in Sentinel-2 imagery are addressed through meticulous manual verification. The updated dataset, covering 13,000 turbine locations, is accessible via the project's data repository, with an interactive map plugin for user engagement.

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1		VRIJE UNIVERSITEIT BRUSSEL	VUB	Belgium
2		DANMARKS TEKNISKE UNIVERSITET	DTU	Denmark
3		INTERNATIONALES INSTITUT FUER ANGEWANDTE SYSTEMANALYSE	IIASA	Austria
4		UNIVERSITAET FUER BODENKULTUR WIEN	BOKU	Austria
5		UNIVERSITETET I OSLO	UiO	Norway
6		NAZKA MAPPS BVBA	NAZKA	Belgium
7		KELSO INSTITUTE EUROPE GEMEINNUTZIGE GMBH	KIE	Germany
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13		MULTICONSULT NORGE AS	MCN	Norway
14		EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	ETH Zürich	Switzerland
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ABBREVIATIONS

Acronym	Description
EEA	European Environment Agency
EU	European Union
GLO	Copernicus global digital surface model
GW	Gigawatt
NUTS	Nomenclature of territorial units for statistics
OSM	OpenStreetMap

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EXECUTIVE SUMMARY

By 2023, Europe boasts 272 GW of installed wind capacity, with 232 GW onshore (EU: 201 GW) and 34 GW offshore (EU: 19 GW). The WindEurope 2024 report projects over 16,000 new onshore and 5,000 offshore wind installations in the coming year, with numbers expected to rise throughout the decade. This growth underscores the need to assess the impacts of these installations on both land and sea.

The "Land & Sea Use and Change Maps" deliverable, part of the WIMBY (Wind in My Backyard) project funded by the EU's Horizon Europe program, aims to enhance social awareness and engagement concerning large wind power installations. The initial report, "Deliverable D1.3: Land & Sea Use and Change Maps," analysed land and sea use changes using Copernicus Sentinel-2 satellite images from 2015 to 2023. The second version builds upon this foundation, focusing on updated methodologies, improved algorithms, additional geographical areas, and refined statistical methods.

1. Introduction

1.1 Key Updates and Enhancements

The initial analysis covered wind turbines installed between 2015 and 2024 in Austria, Denmark, Italy, Norway, and Portugal. The second version extends coverage to include Belgium, France, Germany, Ireland, Luxembourg, Netherlands, Spain, and the UK. As of May 2024, Europe has more than 100,000 onshore turbines, with the analysed countries representing 88% of this total. Spain and Germany alone account for 50% of all European onshore turbines.

The new methodology has significantly increased the speed and accuracy of change detection analysis, allowing for the inclusion of more countries. This involves a refined approach to selecting suitable timeframes for analysis, mainly avoiding periods of snow cover and focusing on early spring or autumn. The improvements also address country-specific conditions, enhancing the overall reliability of the analysis.

The report introduces a dynamic approach to geostatistical analysis, integrating buffer polygons, land cover data, terrain models, and biogeographical regions. This allows for a more nuanced understanding of landscape dynamics around wind turbines and parks. The analysis now dynamically calculates buffer sizes based on the average turbine distance within wind parks, offering a more precise assessment of land cover changes and environmental impacts.

The updated report incorporates the GLO-90 dataset for slope determination and TRI (Terrain Ruggedness Index) classification, reflecting terrain complexity and its ecological implications. European biogeographical regions and ecoregions are used to classify turbine locations, providing insights into biodiversity and conservation efforts.

Offshore wind farm analysis relies on literature and empirical data due to the limitations of satellite imagery in underwater environments. The impact of offshore wind farms on marine ecosystems, sediment dynamics, and seabed geomorphology is assessed using bathymetry data and seabed habitats. The analysis includes both fixed-bottom and floating wind turbines, highlighting their ecological and environmental implications.

1.2 Challenges and Obstacles

OpenStreetMap (OSM) data inaccuracies presented challenges, with approximately 10% of turbines showing significant location deviations. Manual verification was necessary to ensure accurate analysis.

Spatial inconsistencies in Sentinel-2 imagery required manual control and adjustment to align successive images accurately. This step was crucial for maintaining the reliability of change detection analysis.

1.3 Results and Output

The updated dataset, covering 13,000 turbine locations in various European countries, is available on the project's data repository. Additionally, a plugin for the Interactive Map (T5.2) provides users with direct access to the compiled data, enhancing the utility of the statistical information.

2. PREFACE

By 2023 Europe has 272 GW of installed wind capacity, 232 GW onshore (EU: 201 GW) and 34 GW offshore (EU: 19 GW), while it is expected that two thirds of the new wind installations up to 2030 will continue to be onshore. For 2024 for all of Europe more than 16.000 installations of onshore and 5000 offshore wind turbines are to be expected (WindEurope, 2024), with even increasing installation numbers until the end of the decade. These figures make it clear that it is of paramount interest to assess the implications of these installations, including the expected changes on-land, but also off-shore.

This section serves as the preface to the second version of the "Land & Sea Use and Change Maps" deliverable, which is part of the WIMBY (Wind in My Backyard) project. This project, funded by the European Union's Horizon Europe research and innovation program, aims to utilize holistic modelling tools to advance social awareness and engagement concerning large wind power installations across the European Union.

The initial version of this report, titled "Deliverable D1.3: Land & Sea Use and Change Maps," provided a comprehensive description of the analysis based on various data sources, including Copernicus Sentinel-2 satellite images from 2015 to 2023. It detailed the methodologies and results of change detection algorithms developed to monitor land and sea use changes around wind turbine installations. This dataset is essential for numerous tasks within the project.

In this second version, we aim to build upon the foundation laid by the first report. The primary focus is to highlight and document the differences and updates that have emerged since the initial publication. These changes include adapted methodology for data analyses, improved algorithms, additional geographical areas, and refined statistical methodologies. Specifically, the new report captures updates such as:

- Extended data analysis covering additional EU countries beyond countries with WIMBY pilot cases: Austria, Italy, Norway, and Portugal.
- Enhancements in the change detection.
- Advanced statistical analyses for recently built wind turbines and wind parks.
- Updates in environmental and terrain data integrations.

- Description of the methodology to statistically analyse offshore facilities.

This approach ensures that stakeholders, researchers, and policymakers can efficiently track progress and updates without revisiting the entire original document. It facilitates a clearer understanding of advancements and adjustments made in response to new data and insights.

The structure of the second version mirrors that of the first, with sections dedicated to updated materials and methods, new data results, and revised conclusions. Each section explicitly indicates where changes have been made, providing a transparent and coherent view of the task's progression. By focusing on the differences and updates, this document ensures that all advancements and modifications are clearly communicated, maintaining the integrity and continuity of the original report while reflecting the dynamic nature of the analyses.

The authors trust that this revised report serves as a valuable resource for understanding land and sea use changes in the context of wind power development and will aid in the ongoing efforts to foster sustainable and socially engaged energy solutions in the European Union.

3. CHANGES AND ADDITIONS

3.1 Extended data coverage

The first report was based on the analysis of Sentinel-2 data of wind turbines build between 2015 and 2024 in Austria, Denmark, Italy, Norway and Portugal. Until May 2024 the change detection algorithm processed additional countries: Belgium, France, Germany, Ireland, Luxembourg, Netherlands, Spain and the United Kingdom.

Figure 1 visualizes the data coverage by May 2024, with blue-coloured countries which have been processed and green countries which are subject to be processed beyond the project scope. The number for each country indicates the total number of turbines, whereas for already processed countries also show the number of turbines that have been installed since 2015 and which could therefore be evaluated in the change detection analysis. In general, the numbers show that in Europe (EU plus UK, Norway and Switzerland) more than 100.000 onshore turbines are installed

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and countries already analysed provide about 88% of all turbines, and in particular Spain and Germany together account for 50% of all European onshore turbines.

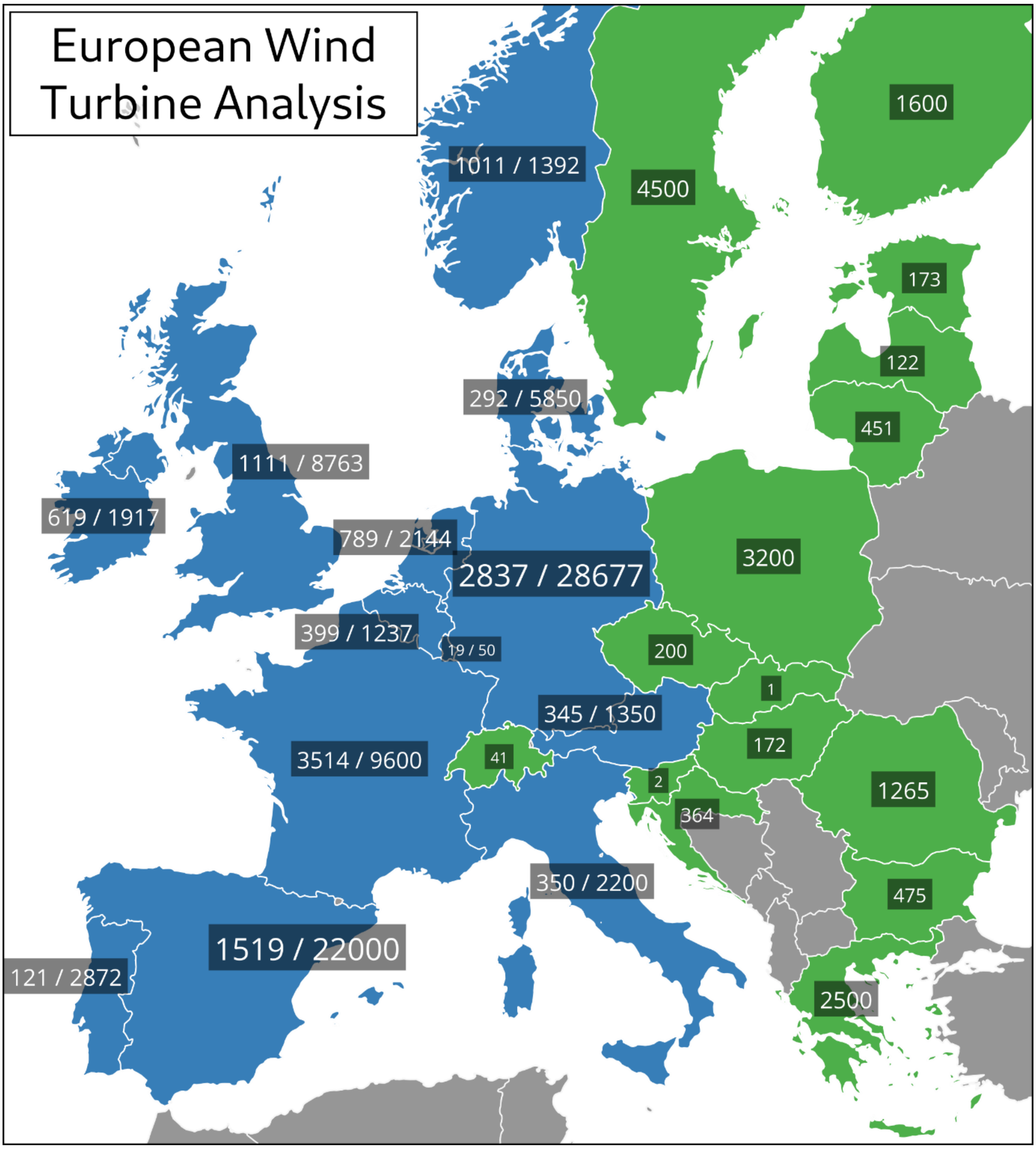

Figure 1. Satellite data analysis coverage overview by end of May 2024, blue-coloured countries have been processed in course of the project, green ones which are additionally processed beyond the project. For all countries to total number of onshore turbines is available, for already processed countries also the number of analysed turbines.

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Table 1 displays the numbers visualized in Figure 1 for all countries already processed by the change detection algorithm. Additionally, the percentage share of new turbines from 2015 onward is shown.

Table 1. Currently analysed countries with the total amount of turbines, turbines built after 2015, and the share of new turbines in percent.

Country	Turbines total	Turbines new	Share of new turbines (%)
Austria	1,350	345	25.6
Belgium	1,237	399	32.3
Denmark	5,859	292	5.0
France	9,600	3,514	36.6
Germany	28,677	2,837	9.9
Ireland	1,917	619	32.3
Italy	2,200	350	15.9
Luxembourg	50	19	38.0
Netherlands	2,144	789	36.8
Norway	1,392	1,011	72.6
Portugal	2,872	121	4.2
Spain	22,000	1,519	6.9
United Kingdom	8,763	1,111	12.7
Total	**88,061**	**12,926**	**14.7**

3.2 Change detection enhancements

While analysing the first countries (Austria, Denmark, Italy, Norway and Portugal) until December 2023 (first reporting period) still required a lot of fine-tuning and manual work, the speed of the whole change detection analysis was significantly increased on the basis of the experience during the process of these first countries. In particular, country-specific circumstances could be better addressed and a suitable time window for the comparison could be found more quickly. Choosing the suitable time period for the analyses mainly refers to vegetation period and avoidance of snow cover. Essentially, the analysis tries to find the earliest timeframe in a year with no (or as few) snow cover as possible, starting from January. If it is not possible to find a suitable timeframe before the vegetation period is too far advanced, also dates in autumn are analysed for suitability. This speed up led to the decision to include even more countries in the analysis.

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3.3 Advances in statistical analyses

As described in the first report of this dataset, our study presents a comprehensive geostatistical analysis integrating buffer polygons, land cover data, terrain models, and biogeographical regions to elucidate spatial patterns and environmental relationships. The approach leverages buffer polygons to delineate zones of influence around single wind turbines and entire wind parks, facilitating the examination of land cover variations within these zones. In contrast to the previous version, we calculate the buffer sizes dynamically, based on the average turbine distance within one wind park. An example of different buffer sizes for wind park clusters can be viewed in Figure 2.

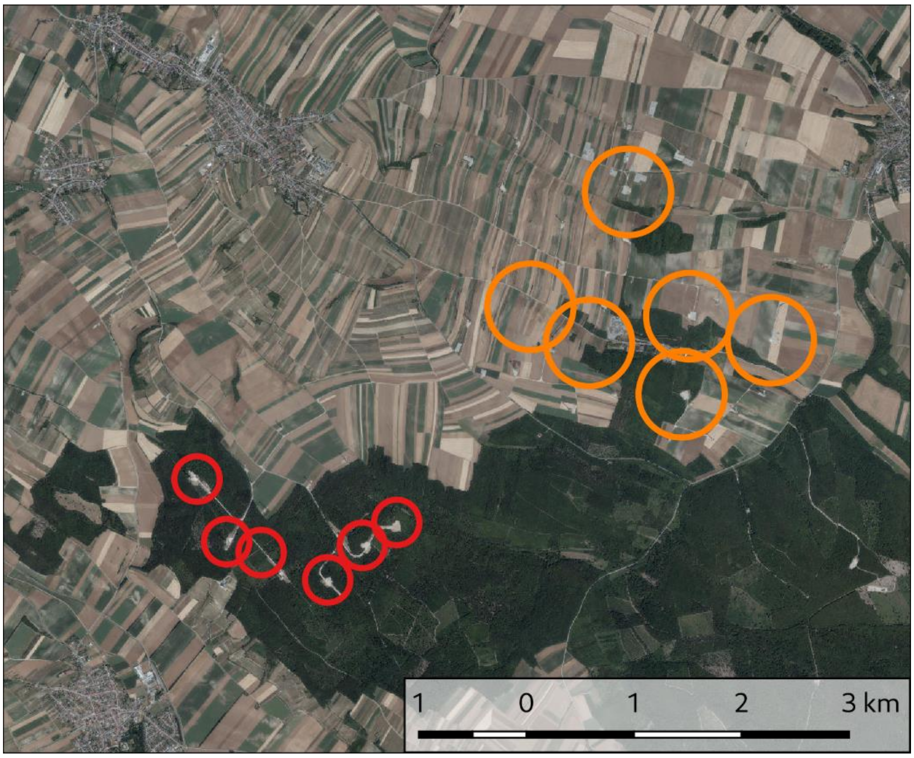

Figure 2. Dynamic buffer sizes for wind park clusters

By incorporating the terrain and eco- & biogeographical regions, the analysis accounts for geographical, ecological and climatic heterogeneity, enabling a nuanced understanding of landscape dynamics. The results in the dataset underscore the significance of the terrain and biogeographical context in shaping land cover change patterns, revealing distinct distributions along these regions. This integrated methodology offers valuable insights for landscape management, conservation planning, and environmental monitoring, highlighting the interplay between spatial configuration, ecological processes, and biogeographical diversity.

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As opposed to the dataset described in the first version of the report we use terrain data, i.e. altitude, slope and ruggedness (Beasom et al., 1983), and biogeographical regions to classify existing political boundaries (i.e. NUTS3 regions), and deviate from this static methodology to a more dynamic and accurate approach: on the one hand the differences of landscapes within the rigid boundaries of the NUTS3 regions can be significant, on the other hand availability of turbines between 2015 and today is scarce for large regions in Europe in most countries. This might be because of the absence of turbines in general, but also because the turbines were erected before 2015, not allowing for an analysis utilizing Sentinel-2 satellite imagery. Hence, the original approach would have resulted in a statistically problematic outcome. The adapted approach circumvents this issue.

With the adapted approach each wind turbine and wind park used in the analysis are provided with data regarding country, land cover types and shares, altitude, slope, ruggedness and biogeographical regions, and additionally the shape description of the parks. Instead of imprinting the aggregated data on a whole NUTS-3 region, we look for similarities in landscapes based on the data mentioned above. This leads to a data set created on a European scale, based on the aforementioned criteria, with the objective of assessing the impact of land use changes on the viability of future planned wind farms.

The data was shared with our partners in WP1 to further improving the integration of this data in the respective tasks. A significant degree of focus was placed on the provision of data for the Interactive Map (T5.3), with the development of a bespoke Python based appliance designed to ensure the accuracy and reliability of the data presented to users. Both the code for the automatic statistical assessment and the library for the integration with the Interactive Map is currently under internal review and will then be shared under an open license publicly.

3.1 Terrain & Ecoregion dataset updates

3.1.1 Terrain datasets

As outlined in the first report, the GLO-90 dataset is employed (European Space Agency & Airbus, 2022). This dataset was further processed in order to determine the slope and to classify the turbine locations with regard to the TRI (Beasom et al., 1983) by our partners from DTU in course of task T1.1 and is also used in the Interactive Map. The TRI ensures that terrain heterogeneity is not only determined selectively, but also recorded over a larger area. It quantifies elevation variability, reflecting terrain complexity. It plays a crucial role in ecological studies by highlighting how varied terrains create diverse habitats that support higher species richness and abundance (Amatulli et al., 2018). Rugged terrains offer multiple niches and reduce competition but can also restrict species movement, leading to isolated populations and reduced genetic diversity (Dilts et al., 2023). Conversely, flatter areas may support less diverse ecosystems. Understanding TRI's impact on species abundance is essential for conservation, helping to identify ecologically valuable and vulnerable areas, and guiding biodiversity preservation and ecosystem management efforts.

3.1.2 Biogeographical and Ecoregion datasets

European biogeographical regions and ecoregions are distinct ecological zones with unique climates, geographies, and biological communities. These classifications, including regions like the Alpine, Atlantic, Boreal, and Mediterranean, are vital for understanding biodiversity and guiding conservation efforts. Ecoregions offer a more detailed look at specific habitats and ecological processes within these broader areas.

In the current analysis four datasets are used to classify the turbine and wind farm locations. For onshore turbines we use the EEA biogeographical regions (European Environment Agency, 2017a) and EEA ecoregions (European Environment Agency, 2017b), as well as the dataset for environmental stratification of Europe (Metzger, 2018).

3.2Offshore analysis methodology

As mentioned in the first version of the report, there is no possibility to assess underwater changes below and around offshore wind parks via satellite imagery. Hence, we have to rely on existing literature and the empirical data and values already collected and presented by others.

It is evident that the construction, operation, and maintenance of offshore wind farms exert a profound impact on marine ecosystems (C. Li et al., 2023), sediment dynamics, and the geomorphology of the seafloor (Bailey et al., 2014). The installation of offshore wind turbines involves substantial construction activities that can disturb the seafloor (Degraer et al., 2021). The most common foundation types, monopile and jacket foundations, require significant seabed preparation. Monopile foundations involve driving large steel piles deep into the seabed, which can displace and resuspend sediments (Sánchez et al., 2019; Snyder & Kaiser, 2009). This process can lead to increased turbidity, which impacts water quality and marine life (Chakrabarti, 2008). Sediment resuspension can smother benthic habitats, affecting organisms such as molluscs, worms, and other invertebrates that form the basis of the marine food web (Bailey et al., 2014; Perrow et al., 2011). Furthermore, the construction of offshore wind parks can alter sediment transport patterns. The physical presence of turbine foundations and associated structures, such as scour protection (rocks or mats placed around the base of turbines to prevent erosion), can modify local hydrodynamics (Wu et al., 2019; Wyns, 2023). Such alterations can result in alterations to sediment deposition and erosion rates, which may give rise to the formation of new seabed features while eroding others. Over time, these changes can lead to the reshaping of the underwater landscape, which may affect the distribution of marine species and the habitats they occupy (Inger et al., 2009; Lindeboom et al., 2011). The construction of offshore wind parks can result in the formation of artificial reefs, which can attract fish and other marine species, creating new feeding and breeding grounds. Studies have demonstrated that these areas can become hotspots for marine life, benefiting both the ecosystem and local fisheries (Bergström et al., 2013; Degraer et al., 2021; Raoux et al., 2017). However, the ecological value of these artificial reefs is contingent upon a number of factors, including the design of the structures, the pre-existing environmental conditions, and the level of ongoing human disturbance.

Within this task we perform an analysis similar to the onshore analysis:

- Single turbines with buffer zones around the turbine location
- Windpark analysis with enveloping concave / convex hull

The data used are similar as the one used for the onshore assessment: altitude, slope and ruggedness from bathymetry data (EMODnet Bathymetry Consortium, 2022) as well as the inclusion of seabed habitats (Vasquez et al., 2020). In conjunction with the empirical data from the aforementioned literature, we are also able to provide estimates of changes in the state of the seabed for future parks.

A special case is that of floating wind farms. The first commercial-scale floating wind farm, Hywind Scotland, has demonstrated the feasibility and potential of this technology, achieving high-capacity factors and operational success in challenging marine environments (Equinor, 2018).

Unlike fixed-bottom turbines, floating wind turbines are anchored to the seabed with mooring lines and can be installed in waters deeper than 60 meters. However, the technology faces significant engineering and economic challenges, including the need for robust and reliable mooring systems, dynamic cable management, and increased installation and maintenance costs (Degraer et al., 2021). Similar to the approach with offshore turbines installed with foundations, we provide an estimation on seabed changes due to the installation of floating turbines, mainly the estimation of mooring installations on the seabed.

4. Difficulties and Obstacles

4.1 OSM Accuracy

OpenStreetMap (OSM) is a collaborative project that provides free and editable maps of the world, relying on voluntary contributions from users. While OSM has become a vital resource for various applications, its accuracy and reliability can be inconsistent due to its crowdsourced nature. Inaccurate OSM data can arise from multiple sources, including human error, outdated information, and varying levels of contributor expertise. Such inaccuracies can have a significant impact on applications that rely on precise geospatial data, including navigation systems, disaster response, urban planning, and geographic research (Haklay, 2010).

During our research we faced inaccuracies in both turbine locations and missing turbines in general. Our analysis shows that approximately 10% of all turbines exhibit a displacement exceeding 10 metres, with some turbines exhibiting a deviation of over 50 metres from the intended location. This significant discrepancy renders an automated analysis with Sentinel-2 data impractical. These issues required manual recheck of all turbines located in OSM.

4.2 Sentinel-2 Shift

Sentinel-2, a component of the European Space Agency's Copernicus programme, provides high-resolution multispectral imagery that is of great value in a number of applications, including agriculture, forestry, and environmental monitoring. However, the data obtained from Sentinel-2 can undergo changes with each flyover, which can present challenges for

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consistent analysis and accurate temporal comparisons. These changes, which are caused by a number of factors, including orbital variations, sensor alignment discrepancies, and atmospheric conditions, can result in misalignments between successive images. Such spatial inconsistencies present challenges for tasks such as change detection, multi-temporal analysis, and precise mapping (J. Li & Roy, 2017). The impact of these shifts is particularly pronounced in applications requiring high positional accuracy, where even minor misalignments can result in significant errors. Techniques to mitigate these issues include rigorous geometric correction processes, co-registration algorithms, and the use of ground control points to align images accurately. It is of the utmost importance to pursue continuous improvement in sensor calibration and image processing methodologies in order to enhance the reliability and usability of Sentinel-2 data for various scientific and operational applications (Gascon et al., 2017). These issues have made the analysis of the Sentinel-2 imagery during the change-detection process more challenging. Therefore, manual control and intervention were necessary, essentially a visual comparison of the two tiles is made and a shift for a perfect overlap performed.

5. Conclusions

In this updated version of the "Land & Sea Use and Change Maps" report, we have made significant strides in understanding the impact of wind energy installations on European land- and seascapes. The expanded data coverage and enhanced methodologies detailed in this document reflect our commitment to continuously improving the accuracy and depth of our analysis. By extending the scope of our research to include most European countries and refining our change detection and statistical analysis techniques, we provide a more comprehensive overview of the evolving wind energy landscape.

The report underscores the complexity and dynamism of land and sea use changes in the context of wind turbine installations. Through the incorporation of updated datasets and the application of advanced geostatistical methods, we offer new insights into the environmental impacts of wind power development. The extended analysis of both onshore and offshore installations reveals critical interactions between wind energy infrastructure and ecological as well as geological features,

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enhancing our ability to make informed decisions for sustainable energy practices.

Our findings highlight the necessity for precise and adaptive approaches in monitoring and managing the implications of wind energy projects. The documented challenges, such as data accuracy from OpenStreetMap and spatial inconsistencies in Sentinel-2 imagery, emphasize the need for meticulous manual verification and the continuous development of robust analytical tools. Addressing these issues is vital for maintaining the integrity of our assessments and ensuring the reliability of the data we provide to our project partners and stakeholders.

6. Results and Output

The resulting data is currently finalized and both raw data (i.e. change tiles) and the statistically processed vector data are made available on the projects data repository under http://yoda.uu.nl. The raw change detection data tiles (binary geotiff files) cover the aforementioned countries: Austria, Belgium, France, Germany, Italy, Ireland, Luxembourg, Netherlands, Norway, Spain and the United Kingdom, with a total of 13.000 analysed turbine locations.
Additionally statistical data based on country and region (NUTS) were produced and uploaded for further usage. Data samples are presented in the Annex (page 26) for two different regions: one that is relatively flat, one a predominantly agricultural and densely populated character; and another that is characterised by a mountainous topography, with a sparse population density and a high degree of proximity to natural environments. Even though, the pure static statistically processed data is sufficient to cover the objectives of the task a plugin for T5.2 - "Interactive Map," is developed with the objective of furnishing users with direct access to the compiled data, as opposed to merely offering static statistical information. Based on the user input, the plugin will fetch background data (Elevation, Slope, Ruggedness and LandCover) and provide change detection results from a best matching existing wind park.

The code for the analyses is open source and can be found at https://github.com/inwe-boku/WIMBY.

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REFERENCES

Amatulli, G., Domisch, S., Tuanmu, M.-N., Parmentier, B., Ranipeta, A., Malczyk, J., & Jetz, W. (2018). A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. *Scientific Data*, *5*(1), 180040. https://doi.org/10.1038/sdata.2018.40

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future. *Aquatic Biosystems*, *10*(1), 8. https://doi.org/10.1186/2046-9063-10-8

Beasom, S. L., Wiggers, E. P., & Giardino, J. R. (1983). A Technique for Assessing Land Surface Ruggedness. *The Journal of Wildlife Management*, *47*(4), 1163. https://doi.org/10.2307/3808184

Bergström, L., Sundqvist, F., & Bergström, U. (2013). Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progress Series*, *485*, 199–210. https://doi.org/10.3354/meps10344

Chakrabarti, S. (2008). *Handbook of offshore engineering. 1* (Repr). Elsevier.

Degraer, S., Brabant, R., & Rumes, B. (Eds.). (2021). *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Attraction, avoidance and habitat use at various spatial scales*. Royal Belgian Institute of Natural Sciences.

Dilts, T. E., Blum, M. E., Shoemaker, K. T., Weisberg, P. J., & Stewart, K. M. (2023). Improved topographic ruggedness indices more accurately model fine-scale ecological patterns. *Landscape Ecology*, *38*(6), 1395–1410. https://doi.org/10.1007/s10980-023-01646-6

EMODnet Bathymetry Consortium. (2022). *EMODnet Digital Bathymetry (DTM 2022)* [GeoTIFF,NetCDF,XYZ File]. EMODnet Bathymetry Consortium. https://doi.org/10.12770/FF3AFF8A-CFF1-44A3-A2C8-1910BF109F85

Equinor. (2018). *Hywind Scotland: World's first floating wind farm.* https://www.equinor.com/en/what-we-do/floating-wind.html

European Environment Agency. (2017a). *EEA biogeographical regions dataset.* https://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-3

European Environment Agency. (2017b). *EEA ecoregions dataset.* https://www.eea.europa.eu/data-and-maps/data/ecoregions

European Space Agency & Airbus. (2022). *Copernicus DEM* [dataset]. https://doi.org/10.5270/ESA-c5d3d65

Gascon, F., Bouzinac, C., Thépaut, O., Jung, M., Francesconi, B., Louis, J., Lonjou, V., Lafrance, B., Massera, S., Gaudel-Vacaresse, A., Languille, F., Alhammoud, B., Viallefont, F., Pflug, B., Bieniarz, J., Clerc, S., Pessiot, L., Trémas, T., Cadau, E., … Fernandez, V. (2017). Copernicus Sentinel-2A Calibration and Products Validation Status. *Remote Sensing*, *9*(6), 584. https://doi.org/10.3390/rs9060584

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Haklay, M. (2010). How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets. *Environment and Planning B: Planning and Design*, *37*(4), 682–703. https://doi.org/10.1068/b35097

Inger, R., Attrill, M. J., Bearhop, S., Broderick, A. C., James Grecian, W., Hodgson, D. J., Mills, C., Sheehan, E., Votier, S. C., Witt, M. J., & Godley, B. J. (2009). Marine renewable energy: Potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology*, *46*(6), 1145–1153. https://doi.org/10.1111/j.1365-2664.2009.01697.x

Li, C., Coolen, J. W. P., Scherer, L., Mogollón, J. M., Braeckman, U., Vanaverbeke, J., Tukker, A., & Steubing, B. (2023). Offshore Wind Energy and Marine Biodiversity in the North Sea: Life Cycle Impact Assessment for Benthic Communities. *Environmental Science & Technology*, *57*(16), 6455–6464. https://doi.org/10.1021/acs.est.2c07797

Li, J., & Roy, D. (2017). A Global Analysis of Sentinel-2A, Sentinel-2B and Landsat-8 Data Revisit Intervals and Implications for Terrestrial Monitoring. *Remote Sensing*, *9*(9), 902. https://doi.org/10.3390/rs9090902

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., De Haan, D., Dirksen, S., Van Hal, R., Hille Ris Lambers, R., Ter Hofstede, R., Krijgsveld, K. L., Leopold, M., & Scheidat, M. (2011). Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters*, *6*(3), 035101. https://doi.org/10.1088/1748-9326/6/3/035101

Metzger, M. J. (2018). *The Environmental Stratification of Europe* [dataset]. University of Edinburgh. https://doi.org/10.7488/DS/2356

Perrow, M. R., Gilroy, J. J., Skeate, E. R., & Tomlinson, M. L. (2011). Effects of the construction of Scroby Sands offshore wind farm on the prey base of Little tern Sternula albifrons at its most important UK colony. *Marine Pollution Bulletin*, *62*(8), 1661–1670. https://doi.org/10.1016/j.marpolbul.2011.06.010

Raoux, A., Tecchio, S., Pezy, J.-P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M., Grangeré, K., Le Loc'h, F., Dauvin, J.-C., & Niquil, N. (2017). Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning? *Ecological Indicators*, *72*, 33–46. https://doi.org/10.1016/j.ecolind.2016.07.037

Sánchez, S., López-Gutiérrez, J.-S., Negro, V., & Esteban, M. D. (2019). Foundations in Offshore Wind Farms: Evolution, Characteristics and Range of Use. Analysis of Main Dimensional Parameters in Monopile Foundations. *Journal of Marine Science and Engineering*, *7*(12), 441. https://doi.org/10.3390/jmse7120441

Snyder, B., & Kaiser, M. J. (2009). Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy*, *34*(6), 1567–1578. https://doi.org/10.1016/j.renene.2008.11.015

Vasquez, M., Manca, E., Inghilesi, R., Martin, S., Agnesi, S., Al Hamdani, Z., Annunziatellis, A., Bekkby, T., Pesch, R., Askew, N., Bentes, L., Castle, L., Doncheva, V., Drakopoulou, V., Gonçalves, J., Laamanen, L., Lillis, H., Loukaidi, V., McGrath, F., … Virtanen, E. (2020).

This project has received funding from the European Union's research and innovation programme Horizon Europe under the grant agreement No. 101083460. This document reflects only the author's view, and the Commission is not responsible for any use that may be made of the information it contains

EUSeaMap 2019, A European broad-scale seabed habitat map, technical report [Pdf]. EMODnet. https://doi.org/10.13155/74782

WindEurope. (2024). *Wind energy in Europe—2023 Statistics and the outlook for 2024-2030*. https://proceedings.windeurope.org

Wu, X., Hu, Y., Li, Y., Yang, J., Duan, L., Wang, T., Adcock, T., Jiang, Z., Gao, Z., Lin, Z., Borthwick, A., & Liao, S. (2019). Foundations of offshore wind turbines: A review. *Renewable and Sustainable Energy Reviews*, *104*, 379–393. https://doi.org/10.1016/j.rser.2019.01.012

Wyns, T. (2023). *Belgian offshore wind: Innovation and investment* (National Case Study Report #1). Vrije Universiteit Brussel. https://www.4i-traction.eu/sites/default/files/2023-04/4iT_2023_Case_Study_1_Belgian_offshore_wind.pdf

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ANNEX

Fundamental data

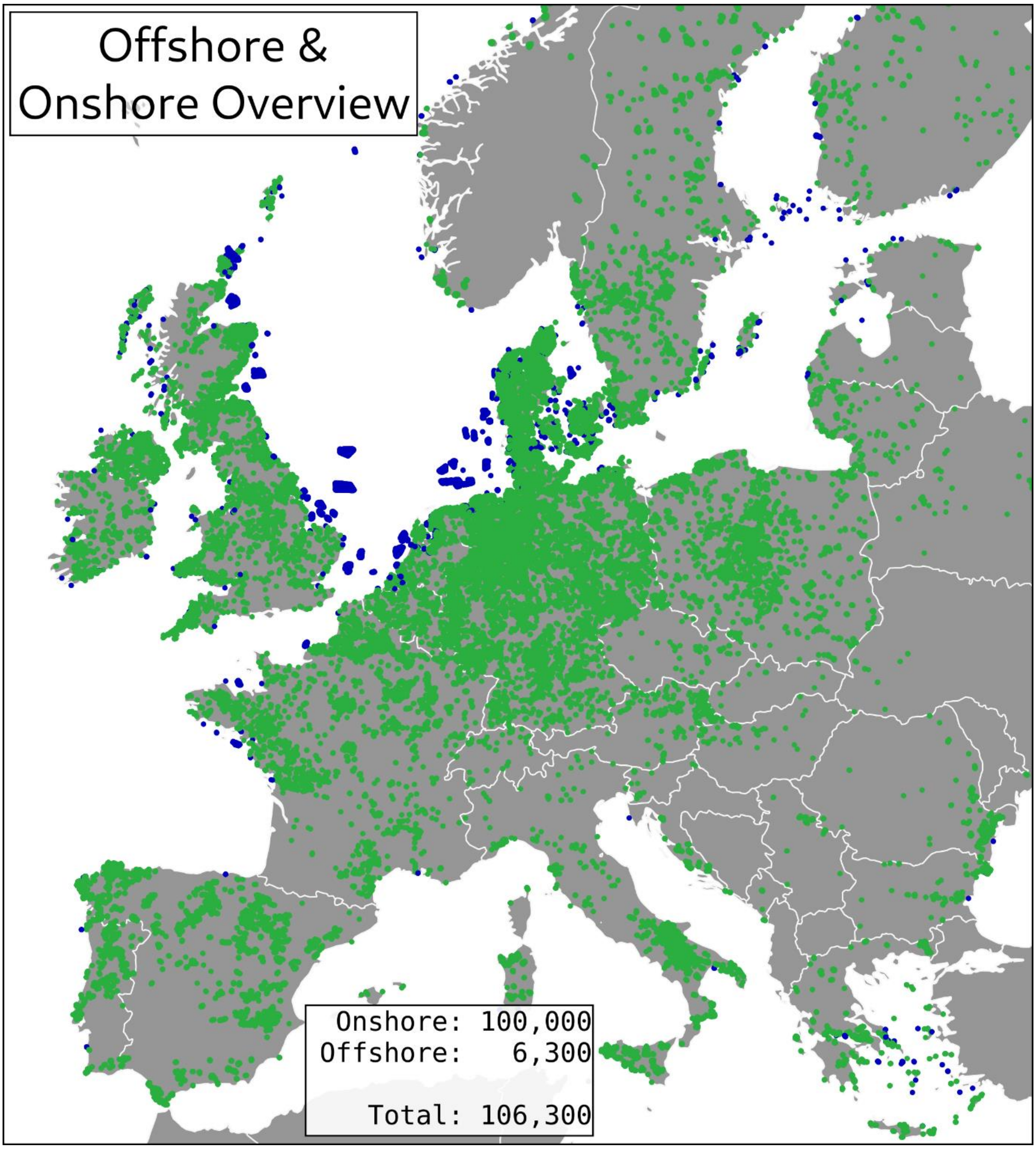

Figure 3. Onshore and offshore turbine distribution in Europe

Figure 3 depicts a spatial distribution map of wind turbine installations across Europe, categorizing them into onshore and offshore types. The onshore installations, denoted by green dots, exhibit a significant concentration in central and western European countries, with notable clusters in Germany, France, Spain and the United Kingdom. Offshore wind turbines, indicated by blue dots, are predominantly situated along the

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continental shelf areas, particularly in the North Sea, the Baltic Sea, and fewer in the Atlantic Ocean near the coasts of Northern and Western Europe.

Exemplary Analysis Output

Table 2 provides a cumliative change detection data analysis based on the 2018 100m Corine Landcover dataset for an populated area, with industrial and agricultural areas, measured in hectares (ha), and the percentage change in area for three different spatial methods: Single Buffer, Concave Hull, and Convex Hull.

The change calculation is based on our analysis of Sentinel-2 satellite imagery at locations before and after the construction of turbines. The results show that most turbines are build on agricultural areas (land use codes 211, 242 and 231), but, in this case, also in industrial areas. The determined demand of area for wind turbines on agricultural areas ranges between 0.4% and 1.0%, while the changes observed in industrial areas are higher. However, this does not necessarily mean that these changes only result from the construction of wind turbines, but also due to other construction within these areas. The interpretation of the results must therefore be carried out with particular caution and in consultation with the tasks using these results.

Table 2. Exemplary Cumulative Corine Landcover Change Analysis e Analysis for an agricultural and pupulated area

Populated and agricultural area	Single Buffer		Concave Hull		Convex Hull	
	Total (ha)	Change (%)	Total (ha)	Change (%)	Total (ha)	Change (%)
211 - Non-irrigated arable land	4003	1,0	5405	0,8	5628	0,8
242 - Complex cultivation patterns	1315	0,5	1778	0,4	1817	0,5
121 - Industrial or commercial units	1114	7,6	1422	6,9	1565	7,4
231 - Pastures	816	0,5	1125	0,4	1130	0,4
123 - Port areas	547	2,5	1059	3,1	1184	3,5
322 - Moors and heathland	220	5,6	362	5,5	392	6,0
243 - Land principally occupied by agriculture with significant areas of natural vegetation	209	1,0	263	0,8	272	0,8
312 - Coniferous forest	204	4,0	371	2,8	376	2,7
313 - Mixed forest	164	0,7	287	0,5	287	0,5
122 - Road and rail networks and associated land	143	0,7	255	0,7	257	0,7
112 – Discontinuous urban fabric	122	1,9	180	1,5	191	1,4
133 - Construction sites	98	4,2	142	2,3	171	2,6
512 - Water bodies	98	4,3	382	1,7	436	1,6

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311 - Broad-leaved forest	79	0,3	114	0,2	114	0,2
142 - Sport and leisure facilities	56	1,5	50	0,8	50	0,8
132 - Dump sites	44	2,6	72	2,5	72	2,5
511 - Water courses	41	1,3	64	3,0	70	3,4
324 - Transitional woodland-shrub	26	3,7	38	5,1	38	5,0
131 - Mineral extraction sites	14	12,7	15	11,8	15	11,8

As above for the agricultural area Table 3 provides change detection statistical data for a region that is sparely populated and in relatively natural state.

The results show that most turbines are build on pristine areas (land use codes 333, 322, 412, 332), and also within forests and sparsely agricultural used areas (243). The determined demand of area for wind turbines on the pristine areas ranges between 1.1% and 5.0% within the different bufferzones. The changes in forests show numbers up to 5.3% and those on agricultural areas stay on low numbers of 0.3%. In contrast to the region shown above, the interpretation of the results is easier, as the influence of other human activities is generally lower.

Table 3. Exemplary Cumulative Corine Landcover Change Analysis e Analysis for a sparsely populated and mostly pristine area

Sparsely populated and mostly pristine area	Single Buffer		Concave Hull		Convex Hull	
	Total (ha)	**Change (%)**	**Total (ha)**	**Change (%)**	**Total (ha)**	**Change (%)**
333 - Sparsely vegetated areas	10262	3,7	19155	2,6	27070	2,0
322 - Moors and heathland	3988	2,7	7783	1,9	12169	1,5
312 - Coniferous forest	3175	5,3	6170	3,7	8238	3,0
412 - Peat bogs	511	5,0	1112	4,0	1544	3,3
243 - Land principally occupied by agriculture with significant areas of natural vegetation	438	0,3	948	0,2	1734	0,1
332 - Bare rocks	289	1,9	463	1,5	653	1,1
324 - Transitional woodland-shrub	272	5,0	604	3,1	896	2,4
311 - Broad-leaved forest	271	2,3	631	1,6	2436	0,8
523 - Sea and ocean	73	0,1	92	0,1	96	0,1
231 - Pastures	56	0,1	85	0,1	101	0,2
211 - Non-irrigated arable land	49	1,5	73	1,1	75	1,0
512 - Water bodies	28	0,5	363	0,2	1324	0,2
423 - Intertidal flats	21	0,7	22	0,7	22	0,7
131 - Mineral extraction sites	15	4,6	71	5,3	118	3,5
242 - Complex cultivation patterns	10	7,2	22	4,2	26	3,6
313 - Mixed forest	5	0,0	57	0,2	331	0,1

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