BLUEWISE MARINE

Site Identification Analysis for Airborne Wind Energy devices

Case Study: The Netherlands

Interreg North-West Europe

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DEM-AWE

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Executive Summary

This report details the site identification analysis for Airborne Wind Energy (AWE) devices in the Netherlands, conducted under the DEM-AWE project. Using Geographic Information Systems (GIS) and publicly available data, the study evaluated site suitability, applying refined criteria and sensitivity analyses to address the Netherlands' unique geographic and logistical characteristics.

Site identification criteria included slope, operational radius, proximity to settlements, and airspace constraints, ensuring adaptability to various AWE technologies. Data from sources including OpenStreetMap, NASA SRTM, and the Nationaal Georegister were integrated into QGIS for analysis. A sensitivity analysis was carried out where parameters including operational radius, risk buffers and distance to forests were varied to assess their impact on land availability. Model outputs were cross-referenced with manual analyses and developer feedback, achieving a 100% match with verified sites.

The base case identified 590–1,270 km² of operational area and 35–115 km² of deployment area which translates to 650 – 1,240 sites and up to 2,810 devices, supporting 1.9–4.2 GW of AWE capacity. Variations in operational radius revealed its significant impact, with shorter radii (e.g., 300 m) enabling greater deployment density. Friesland, Groningen, and Flevoland emerged as the most promising regions due to their flat terrain and agricultural co-use potential, while densely urbanised and varied topography areas like Noord-Holland and Limburg showed lower suitability.

The Netherlands’ high population density (544 people/km²) limits large-scale AWE deployment compared to countries like Ireland and Germany. Results show that operational radius is a critical determinant of deployment potential, necessitating developer-specific optimisations. Data gaps, especially in building classifications, affect analysis precision, highlighting the need for enhanced datasets. This study highlights the need for region-specific adaptations and collaborative approaches to optimise AWE deployment in the Netherlands and beyond.

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List of Abbreviations

AWE	Airborne Wind Energy
CRS	Coordinate reference System
DEM	Digital Elevation Model
ETRS89	European Terrestrial Reference System 1989
EPSG:3035	European Projection System Grid
GS	Ground Station
kW	KiloWatt
MW	MegaWatt
NASA SRTM	NASA Shuttle Radar Topography Mission
NGR	Nationaal Georegister
ODbL	Open Database License
OSGDC	Open-Source GIS Dataset Collection License
OSM	Open Street Map
SRTM	Shuttle Radar Topography Mission
TIFF	Tagged Image File Format
QGIS	Open-source GIS software used for geospatial analysis
WDPA	World Database on Protected Areas

1 Introduction

This report details the methodology followed to identify suitable sites for the development of Airborne Wind Energy (AWE) farms in The Netherlands, using publicly available datasets and GIS tools. The analysis follows the general methodology detailed in *“Site Identification Analysis for AWE Devices. A case study in Germany”* Coca-Tagarro, I. (2023). Some variations to the existing methodology were applied after learnings extracted from the German analysis and the engagement with new developers. These improvements included the inclusion of new sensitivity cases, including variations in the operational radius to capture the effects of shorter tether lengths. Additionally, the wind resource was not considered as a parameter given the results obtained in Germany and being an overly simplistic and restrictive parameter.

This report is one of a suite of reports providing individual analysis results for Ireland, the Netherlands, France and Spain. While the core approach remained consistent across all analysed countries, specific adaptations were made to account for each country's unique characteristics in data and geographic context. The data processing workflow was uniform across the analysed countries. The following sections outline the data sources, feature selection, analysis methodology, quality control procedures, and results of the Dutch-specific analysis.

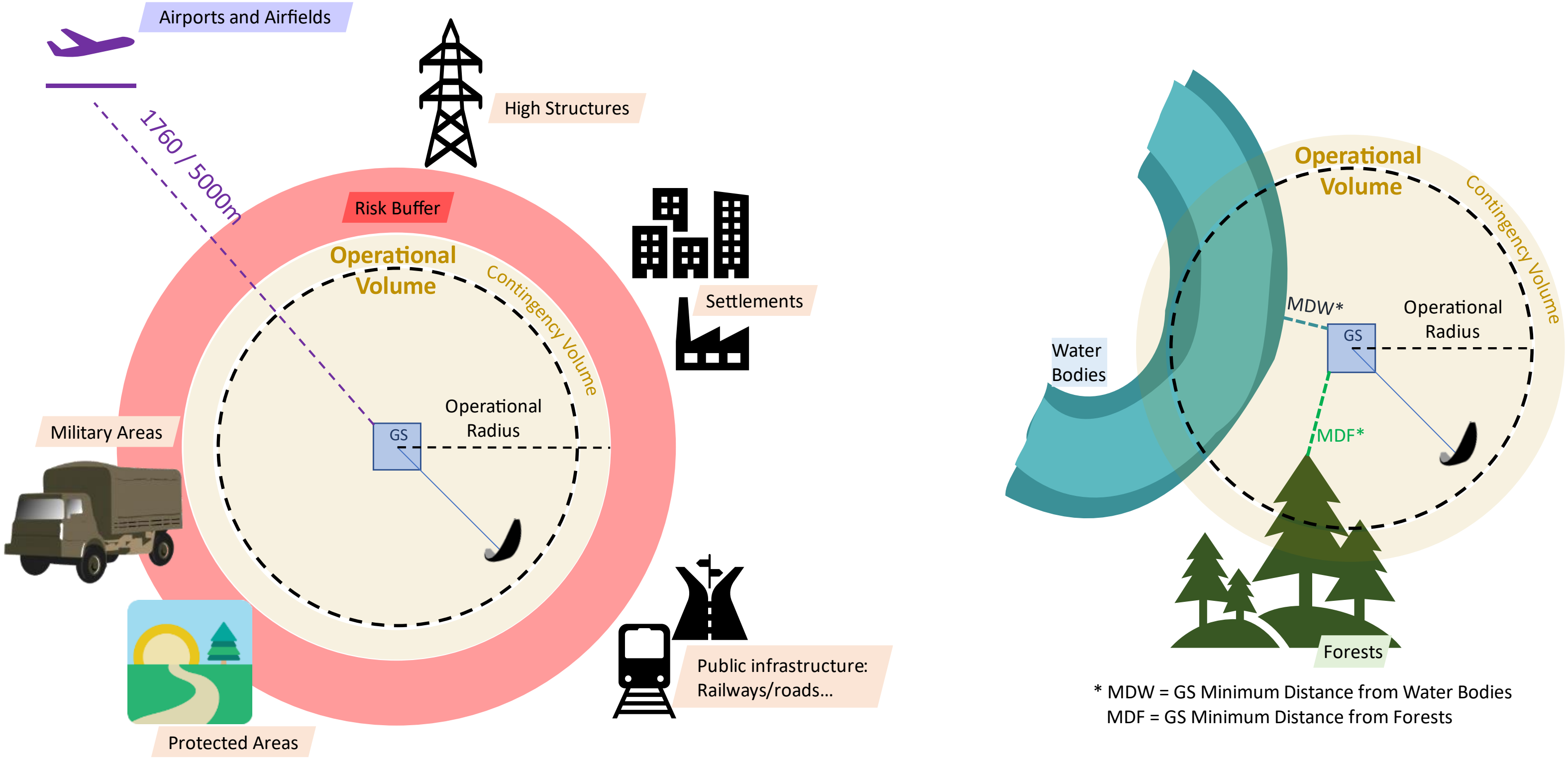
2 Identification Criteria

The criteria for this project were refined and expanded from those used in previous work undertaken as part of the MegaAWE project Coca-Tagarro, I. (2023), originally established through extensive consultations with various industry developers. These engagements led to the development of a number of site identification criteria, specific requirements for AWE devices, and the definition of key parameter variations to conduct sensitivity analyses while maintaining a technology-agnostic approach. This approach seeks to meet the needs and preferences of individual technologies without showing favouritism toward any particular one. It establishes an impartial evaluation framework, offering valuable insights relevant across the industry, encouraging innovation, and supporting well-informed decision-making.

As part of the DEM-AWE project, additional consultations were conducted with further technology developers, resulting in the adjustment of certain criteria and parameters, as well as the addition of sensitivity variations to reflect insights from these discussions and lessons learned from the outcomes observed in Germany. Across both MegaAWE and DEM-AWE projects engagement included consultation with the following technology developers: Enerkite, Kitekraft, Kitepower, Skysails, TwingTec, WindFisher and Ampyx Power (now dissolved but core activity continued by Fuchszeug/Mozaero).

Table 2.1. Criteria, requirements and sensitivity analysis applied to the site identification analysis.

CRITERIA	REQUIREMENT AWE DEVICES	SENSITIVITY STUDIES
Flat in operating and surrounding area	Avoid areas with >30° slope in the deployment areas.	
Co-use, e.g. agricultural land use	Yes	
Operational Radius around ground station	Base Case: 425m	Op. radius: 300, 650,850 and 1050m.
Inhabited urban area/ Settlements in general/ Publicly used infrastructure (e.g., roads, railways)	Avoid. Apply Operational Area radius. Additionally, add Risk buffer. Risk buffer Base Case: 100m distance from Ground Station	Risk buffers: 0, 50, 150m.
High structures (e.g., wind turbines, power lines, phone, met and radio masts)	Avoid. Apply Operational Area radius. 100m Safety buffer around high structures.	
Air Traffic	Avoid. 5000m Risk buffer around Airports. 1760m Risk buffer around Airfields	
Forests	Avoid. Permitted to fly partially over forests. Base Case: 200m distance from Ground Station	Distance from GS: 100 and 300m.
Water bodies	Avoid. Permitted to fly partially over Water Bodies. Base Case Min Distance from Ground Station: 100m.	
Protected Areas Military Areas	Avoid. Apply Operational Area radius	



* MDW = GS Minimum Distance from Water Bodies
MDF = GS Minimum Distance from Forests

Figure 2.1. Diagram on the criteria and requirements applied for the site identification analysis. GS refers to "Ground Station".

3 Data sources and features selection

Identifying suitable locations for AWE systems requires collecting data on environmental, geographical, logistical, and site-specific factors relevant to the technology's requirements.

Several datasets were selected from publicly available sources such as GIS Data Mapog (freely available), NASA Shuttle Radar Topography Mission (SRTM) data managed by NASA JPL (Version 3, 2024)[1], OpenStreetMap contributors (ODbL), the European Union's Copernicus Land Monitoring Service[2], the World Database on Protected Areas[3], UNESCO World Heritage List data (2021, freely available)[4], datasets from the Netherlands' Nationaal Georegister (licensed under CC BY 4.0), and restricted airspace information from Luchtverkeersleiding Nederland (LVNL, freely available for public use). Most of the datasets used were accessed as shapefiles, raster/TIFF (Tagged Image File Format) files or Aviation charts. However, collecting detailed, accurate and current data can be difficult for certain variables, and some data sources present gaps in information (e.g., complete dataset on towers, proper classification on water bodies). An effort was made to obtain at least two different datasets for each criterion to ensure validation and accuracy.

Table 3.1. Main parameters, source and dataset format.

Parameter	Source	Format
Base map	GIS Data Mapog,2024	Shapefiles
Slope	AppEEARS, 2024	TIFF
Protected Areas	World Database on Protected Areas (WDPA), 2024; UNESCO, 2021	Shapefiles

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[1] NASA JPL (2013). NASA Shuttle Radar Topography Mission Global 1 arc second [Data set]. NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC). Accessed 2024-09-23 from https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL1.003

[2] Forest Type dataset, 2018, https://doi.org/10.2909/59b0620c-7bb4-4c82-b3ce-f16715573137, licensed under CC BY 4.0

[3] WDPA, accessed via Protected Planet, licensed under CC BY 4.0

[4] UNESCO World Heritage Centre (2021). World Heritage List. Available at: https://whc.unesco.org [2024-10-16].

Water bodies	Nationaal Georegister (NGR) 2024; OSM, 2024	Shapefiles
Forests	Copernicus, 2024; OSM, 2024	TIFF
Settlements	OSM, 2024	Shapefiles
Military Areas	OSM, 2024	Shapefiles
High structures	Nationaal Georegister (NGR) 2024; OSM, 2024	Shapefiles
Roads	OSM, 2024	Shapefiles
Railways	Nationaal Georegister (NGR) 2024;	Shapefiles
Air Traffic	Luchtverkeersleiding Nederland (LVNL), 2024	Shapefiles, Aviation charts

The data analysis came from the following datasets from which a wide range of data was collected, extracted, and used.

- **GIS Data Mapog:** This resource provided detailed provincial-level geographic data for visualization and spatial analysis, contributing the **basemap layers** to the study.

- **NASA Shuttle Radar Topography Mission (SRTM)**: The SRTM dataset, managed by NASA's Land Processes Distributed Active Archive Center, offers a near-global digital elevation model (DEM) derived from radar interferometry. This dataset, created from data collected during the Space Shuttle Endeavour's STS-99 mission (February 11, 2000), provides elevation information for about 80% of Earth's landmass with a spatial resolution of 1 arc-second (~30 meters). SRTM data fills any voids by merging topographic sources as needed, with version 3 being a void-free global dataset. This data was accessed in March 2024 and was used in the analysis to derive **slope information**.

- **OpenStreetMap (OSM):** OpenStreetMap is a freely accessible, user-contributed geographic database. Volunteers worldwide contribute and maintain its data, ensuring high completeness and accuracy, particularly in European regions. This dataset was used for a wide range of criteria specified in **Error! Reference source not found.**. such as railways, military areas, settlements, etc.

- **Forest Type, EU Copernicus (2018):** This raster dataset offers a forest classification layer with 10-meter spatial resolution, distinguishing three classes: non-forest areas, broadleaved forests, and coniferous forests. Created under the EU Copernicus program by the European Environment Agency in 2020, this High-Resolution Layer Forest Type product aligns with the FAO forest definition.

- **World Database on Protected Areas (WDPA):** Data on protected areas was sourced from the World Database on Protected Areas, accessed via Protected Planet (www.protectedplanet.net). The WDPA is the largest global database of terrestrial and marine protected areas. It includes information on national parks, nature reserves, wilderness areas, community-conserved areas, and other conservation designations. Managed collaboratively by the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) and the International Union for Conservation of Nature (IUCN), the WDPA is central to tracking global biodiversity targets

- **UNESCO (2021):** The UNESCO World Heritage List recognizes and protects cultural, natural, and mixed heritage sites of outstanding universal value, ensuring their preservation for future generations. It is maintained by the United Nations Educational, Scientific and Cultural Organization (UNESCO). Data on the Netherlands UNESCO sites was obtained to include as protected areas.

- **Nationaal georegister:** The Nationaal Georegister (NGR) is the Netherlands' national geographic data portal, providing access to a wide array of geospatial datasets. It is a collaboration between Kadaster (the Dutch Land Registry and Mapping Agency) and other government bodies, aligning with the EU's INSPIRE Directive, which aims to establish a shared framework for spatial data infrastructure across Europe. **Several datasets** specified in Table 3.2 were used.

- **Luchtverkeersleiding Nederland (LVNL):** LVNL is the organization responsible for air traffic control in the Netherlands. It ensures the safe and efficient management of Dutch airspace, facilitating smooth coordination between civil and military aviation while adhering to international aviation standards. Information on **restricted airspace areas** was obtained from this source.

After accessing the datasets, only some of the layers and specific portions of the raw layers were used[5]. To ensure a robust analysis, a thorough process was conducted to determine which layers, and the specific features from each layer, would be included in the input data. The first step involved comparing and cross-checking the information in layers that contained data on the same criteria. Consequently, the features of each layer that aligned with the predetermined selection criteria and parameters were identified. Following this, a thorough visual inspection was conducted on the raw layers and their features, with a minimum of 20 randomly selected features reviewed in three different counties using GIS and satellite imagery. This inspection aimed to confirm whether the layers and the selected features should be retained or excluded from further analysis. Based on the visual inspection and the selection criteria, key features were extracted from each layer and processed (see Section 4) to meet AWE requirements (e.g., identifying relevant high structures and applying safety buffers around them).

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[5] To enhance validation and accuracy, we aimed to acquire at least two datasets for each criterion. However, it was not always necessary to include all the sourced layers in the final analysis. Only the most accurate and complete datasets were retained, or specific parts that complemented other datasets were used.

Table 3.2. Table presenting the selected features from each used dataset.

CRITERIA	Open Street Map (2024)	Others
Airfields and Airports	Transport • Helipad •	NGR (2024)- Vervoersnetwerken: Luchttransport - Transport Networks: Air (INSPIRE geharmoniseerd) • Aerodrome Area • RunwayArea
Base map	N/A	GIS Data Mapog (2024)
Forests	Land Use: • Forest	Copernicus Forest Type (2018) • 1 Broad Leaf Forest • 2 Coniferous Forest
High structures	Points: • Comms_tower • Windmill Power route/Power category Power_towers • Full_id • Osm_id • Osm_type • Route • Wires • Voltage • Operator_w • Frequency • cables	Wind turbines: NGR (2024)- Windturbines - ashoogte Lighthouses: NGR (2024) - Vuurtorens

Military Area	Land Use • Military	N/A
Protected Areas	N/A	WDPA (2024) • Marine Protected Area (OSPAR) • National Park • Nature Conservation act • Nature Reserves • Ramsar site • Wetland of International Importance • Site of Community Importance (Habitats Directive) • Special Protection Area (Birds Directive) • Special Areas of Conservation (Habitats Directive) • UNESCO-MAB Biosphere Reserve • World Heritage Site (natural or mixed) UNESCO (2021) • World Heritage List
Railways	N/A	(NGR) 2024 - Vervoersnetwerken: Spoorwegen - Transport Networks: Rail (INSPIRE geharmoniseerd) Rail
Restricted Airspace	N/A	Luchtverkeersleiding Nederland (LVNL) 2024 Control Zones (CTR)
Roads	Roads • Motorway • Motorway link • Primary • Primary link	

	- Residential - Secondary - Secondary link - Tertiary - Tertiary link - Trunk - Trunk link - Unclassified	N/A
Settlements	Land Use - Allotments - Cemetery - Commercial - Farmyard - Industrial - Park - Recreational Ground - Residential - Retail Buildings - 138 *'type'* categories -see section 4.1.6	N/A
Slope	N/A	AppEEARS (2024) SRTMGL1_DEM (SRTMGL1_NC.003) from NASA Shuttle Radar Topography Mission
Water Bodies	Water - Dock - Reservoir - Riverbank - Water	NGR (2024) - Waterwegen - Vervoersnetwerken (INSPIRE geharmoniseerd) ATOM

4 Data extraction and Site identification methodology using QGIS Models

4.1 Data Collection and Extraction

The data collection for all the different criteria specified in Table 3.1 was carried out utilising various datasets with different characteristics. Some datasets, (e.g. OSM and Copernicus datasets) had a coverage for the entirety of the Netherlands land area. However, the data processing was carried at a provinces level. A QGIS project was created for each one of the provinces. All the data extraction analysis were made using a 5km-buffered base map[6] of the relevant region. The subsections below list every layer, category, and feature utilised for each criterion.

The data extraction of the relevant categories and features of each raw layer was automated using the Graphical Modeller and batch process tool in QGIS. All the inputs from the batch process were stored as .json files to be able to carry out a quality control on this step. The outputs from the Data Extraction process were 11 layers by province containing the relevant data for each criterion. All the layers received a systematic name, containing the criteria, the CRS and the region code ‘XXX’ (E.g, Friesland=FRI):

- Slope_3035_XXX
- Protected_Areas_3035_XXX
- Water_Bodies_3035_XXX
- Forests_3035_XXX
- Settlements_3035_XXX

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[6] A 5 km buffer was added to the base maps of the different regions to account the presence of objects that, even though located outside the state division, could still affect areas within the state or study region due to their predefined range (For example, airports located in an adjacent state, outside the studied region, but which exclusion boundary (5 km) could affect areas within the studied region).

- Settlements2_3035_XXX
- Military_Areas_3035_XXX
- High_Structures_3035_XXX
- RoadsUNC_3035_XXX
- Railways_3035_XXX
- Air_Traffic_3035_XXX

EPSG:3035 (ETRS89, LAEA) was selected as the Coordinate reference system and all raw layers used were reprojected to meet this Coordinate Reference System (CRS). The data extraction steps adopted are detailed in the subsections below.

4.1.1 Base Map

All base maps used were sourced from gisdata.mapog.com in September 2024 (https://gisdata.mapog.com/netherlands/Province%20level%201), which provides open-source geographic data compilations. The data, developed through integration of multiple open-source GIS datasets, complies with the Open-Source GIS Dataset Collection License (Version 1.0) (OSGDC License v1.0) as well as the original licenses governing each data source.

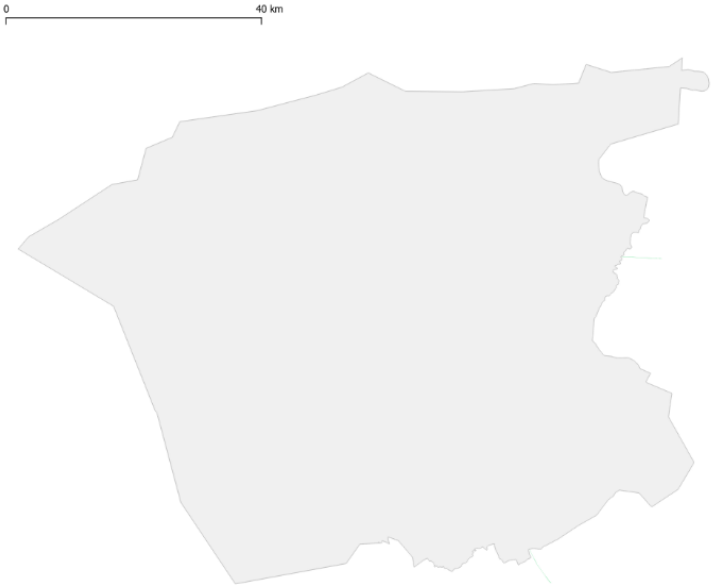

Figure 4.1. Base map. Example: Friesland.
Source Data: GIS Data Mapog (freely available)

4.1.2 Slope

The criteria requirement was to avoid areas with a slope of more than 30 degrees (following the methodology established for this criterion in Germany[7]).

The data used for the slope was extracted in September 2024 from AppEEARS (https://lpdaac.usgs.gov/products/srtmgl1v003/) portal. The layer used "SRTMGL1_DEM (SRTMGL1_NC.003)" was a DEM (Digital Elevation Model) generated by NASA Shuttle Radar Topography Mission, with a pixel size of ~30m.

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[7] Coca-Tagarro, I. (2023). Site Identification Analysis for AWE Devices. A case study in Germany (Version 1). Zenodo. https://doi.org/10.5281/zenodo.10462306

The *Slope* tool was used to calculate the slope in the raster layer. The raster was reclassified[8] using the *raster calculator*, applying the value of 1 to areas with a slope less than 30 degrees and applying a value of 0 to areas with more than 30 degrees. To transform the raster into a vector layer the *polygonize* tool was used and features with a value equal to 0 were erased. The final vector was *clipped* to the Dutch basemap.

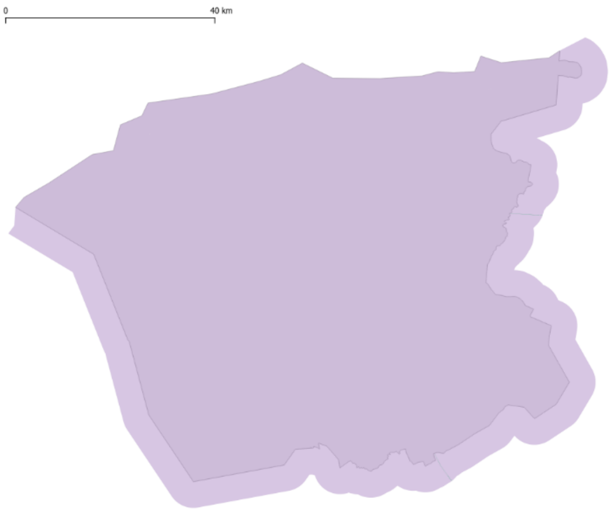

Figure 4.2. Areas in purple meet the slope requirement (<30°). Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©NASA Shuttle Radar Topography Mission (NASA JPL).

Note: No buffer was applied around the excluded slope in order to avoid excluding areas where the GS deployment area is at a higher elevation than the terrain surrounding it. It is expected that the farms at a commercial level can control the deployment and landing of the aircrafts and avoid the terrain with steep slope. Further investigation on a case-by-case basis would be required to identify if GS cannot be deployed in an area that has been identified as “deployment area”.

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[8] Using the following formula; ("Slope3_Fr_3035@1" > 0 AND "Slope3_Fr_3035@1" <= 30)*1 + ("Slope3_Fr_3035@1" > 30) *0)

4.1.3 Protected Areas

The requirement for this criterion was to avoid protected areas and flying over these areas was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m scenarios.

Two data sources were used to extract information on protected areas:

- World Database on Protected Areas (WDPA)[9], being accessed and downloaded in September 2024 from Protected planet (www.protectedplanet.net). The protected areas included: Marine Protected Area (OSPAR), National Park, Nature Conservation Act, Nature Reserves owned by professional nature management organizations, Ramsar Site, Wetland of International Importance, Site of Community Importance (Habitats Directive), Special Areas of Conservation (Habitats Directive), Special Protection Area (Birds Directive), UNESCO-MAB Biosphere Reserve, World Heritage Site (natural or mixed). The data was available to download in three different polygon vector layers that contained the data for all of The Netherlands.
- UNESCO (2021), World Heritage List - A point shapefile containing information about locations of World Heritage Sites globally was accessed and downloaded in October 2024 from userclub.opendatasoft.com. The dataset is published by UNESCO and is available under the Open Database License (ODbL). The data was last modified on March 26, 2021, with the most recent metadata processing occurring on September 19, 2024. The dataset can be accessed through the official UNESCO website at whc.unesco.org/en/list/.

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[9] UNEP-WCMC and IUCN (2024), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], September 2024, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

The layers from the WDPA dataset were *merged* in QGIS and the resulting layer was *clipped* to the correspondent 5km-buffered base map. The UNESCO layer was also clipped to the 5km-buffered base map. A 500m *buffer* was added to account for the extension of the different sites and their buffer zones. Both the WDPA and UNESCO processed layers were merged and the tool *retain fields* was also applied to preserve only identifying fields on

The operational radius was applied in a later stage, specified in section **Error! Reference source not found.** - **Error! Reference source not found.**.

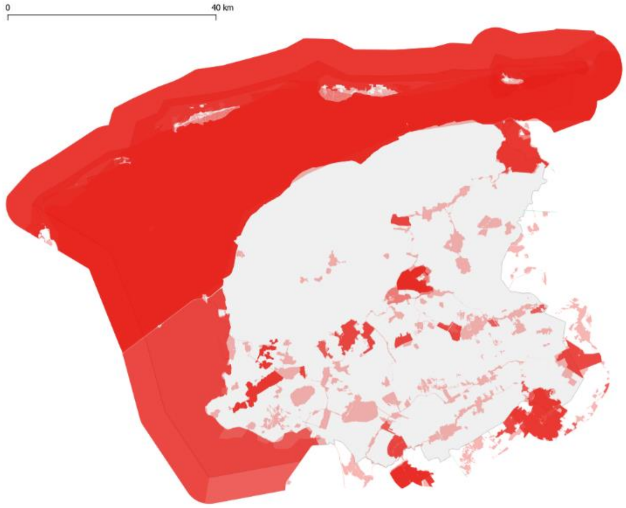

Figure 4.3. Protected Areas (shown in red). Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©World Database on Protected Areas (WDPA, CC BY 4.0), UNESCO (freely available)

4.1.4 Water Bodies

The requirement for this layer was to avoid water bodies as deployment areas and leave a 100m distance to the GS. Flying over these areas is permitted.

The Databases used to obtain data on water bodies in The Netherlands were:

- Waterwegen - Vervoersnetwerken (INSPIRE geharmoniseerd) ATOM - Containing data on Surface water bodies, the dataset was accessed and download in September 2024 from the

National Georegister (NGR). The Land Registry produces and oversees the INSPIRE Transport Networks: Waterways (Transport Networks: Water) theme layer, which is unified and packed with pertinent items from TOP10NL (a component of the Basic Topography Registration BRT).

- OSM (2024) – Water layer, that contains the categories ‘Dock’, ‘Reservoir’, ‘Riverbank’, and ‘Water’.[10] This layer was accessed and downloaded in September 2024 from (https://download.geofabrik.de/)

Retain fields was used on both layers to leave only identifying fields. Both layers were *clipped* to the 5km-buffered basemap and the tool *extract by expression* was used on the OSM dataset to leave obtain only the categories of interest. The output layer was then *merged* to the NGR layer.

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[10] There is no need to include the waterways layer, because this one has already the canal. Rivers and some wide streams (5m wide) incorporated and with the correct width. This layer marks some canals/streams among crop fields. It would be ideal not to include those, but there is no way of filtering the data and this dataset contains some significant water bodies that the official dataset does not contain As we need to include those water bodies, there is no way around not including also some of the streams/canals between crops.

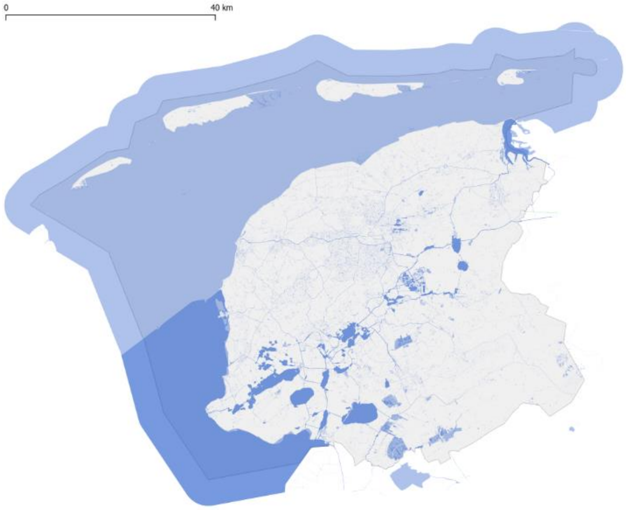


Figure 4.4. Water Bodies (shown in blue). Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL), ©Nationaal Georegister (CC BY 4.0).

4.1.5 Forests

The requirement for this criterion was to avoid forests as deployment areas and leave a 200m distance between the GS and forest cover. Flying over these areas is permitted and sensitivity analysis on the distance to forests includes 100 and 300m scenarios.

Two datasets were used to obtain data on forest coverage:

- The dataset used to obtain data on forests was the Copernicus Forest Type 2018 (raster 10 m Europe, 3-yearly cover), which was accessed and downloaded through Corpernicus's land monitoring service website ([Dataset catalogue — Copernicus Land Monitoring Service](#)) in September 2024. The data was downloaded in raster format, and several layers were downloaded to cover The Netherlands land. The values 1 (Broad leaf forest) and 2 (Coniferous forest) were used.
- The OSM layer on Land use which "fclass" category 'Forests' was used. OSM data was accessed and downloaded from Geofabrik's free download server (https://download.geofabrik.de/) in September 2024.

The *raster calculator* tool was used to extract the areas with the forest cover of interest. All pixels with values less than 1 and greater than 2 were multiplied by 0 and values equal to 1 and 2 were multiplied by 1. The resulting layer was a raster only containing the features 0 and 1. The tool *translate (convert format*) was then used and the 0 feature was assigned a no-data value. The tool *polygonise* was used on the resulting layer to convert the layer from a raster to vector.

The Copernicus dataset and the OSM layer were *merged* and then *clipped* to the 5km-buffered basemap and *retain fields* was used to extract only the fields with identifying values.

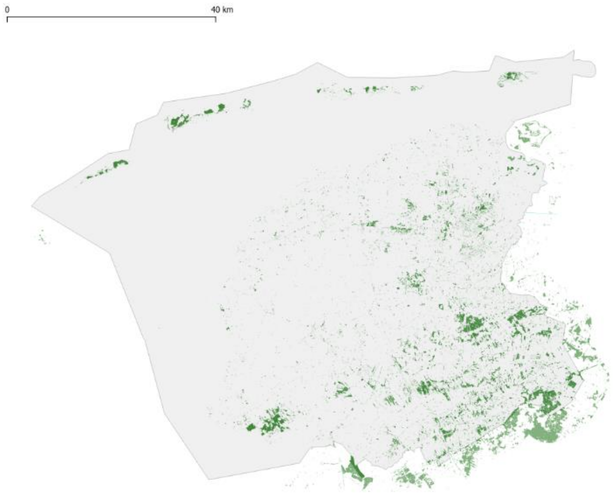


Figure 4.5. Forests (shown in green). Example: Friesland.

Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL), ©Copernicus (CC BY 4.0).

4.1.6 Settlements

The requirement applied to this criterion was to avoid settlements and flying over these areas was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m scenarios. Additionally, a risk buffer of 100m is applied in the base case for this criterion (as part of publicly used infrastructure). Sensitivity analysis on the risk buffer includes 0, 50 and 150m buffers.

The databases used to obtain data on Settlements in The Netherlands were OSM data was accessed and downloaded from Geofabrik's free download server (https://download.geofabrik.de/) in September 2024.:

- The OSM layer on Land use which “fclass” categories ‘Allotments’, ‘Cemetery’, ‘Commercial’, ‘Farmyard’, ‘Industrial’, ‘Park’, ‘Recreation_ground’, ‘Residential’, and ‘Retail’ were used.
- The OSM layer on Buildings. The “type” categories used include: 'allotment_house', 'ambulance_station', 'apartments', 'appartments', 'bakehouse', 'bakery', 'bank', 'barracks', 'basement', 'bell_tower', 'bicycle_parking', 'bungalow', 'cafe', 'carport', 'casemat', 'casemate', 'castle', 'caterer', 'chalet', 'chapel', 'church', 'cinema', 'cityhall', 'civic', 'classroom', 'club', 'clubhouse', 'college', 'colo', 'commercial', 'commercial;house', 'community_centre', 'conference_centre', 'cottage', 'crematorium', 'data_center', 'detached', 'dormitory', 'duiker', 'education', 'elevator', 'events_venue', 'fire_station', 'fortress', 'fuel', 'funeral_hall', 'gate_house', 'glasshouse', 'government', 'government_office', 'grandstand', 'healthcare', 'historical', 'hospital', 'hotel', 'house', 'house;industrial', 'houseboat', 'industrial', 'juvenile_prison', 'kazemat', 'kazemat_fundatie', 'kindergarten', 'kingdom_hall', 'kiosk', 'kitchen', 'lifeguard_tower', 'manufacture', 'military', 'military_hospital', 'mobiel_home', 'mobile unit', 'monastery', 'mosque', 'multifunctional', 'museum', 'nunnery', 'nursing_home', 'office', 'office;commercial', 'orphanage', 'palace', 'parking', 'parking_garage', 'pavilion', 'paviljon', 'plant', 'prefab', 'prison', 'public', 'public_building', 'receptie', 'recreation', 'recreational', 'rectory', 'residential', 'restaurant', 'retail', 'sauna', 'school', 'semidetached_house', 'service', 'shrine', 'social_facility', 'sport', 'sport_canteen', 'sporthal', 'sports', 'sports_centre', 'sports_facility', 'sports_hall', 'stadium', 'static_building', 'static_caravan', 'static_tent', 'station', 'stilt_house', 'stupa', 'supermarket', 'swim_hall', 'swimming_pool', 'synagogue', 'temple', 'terminal', 'terrace', 'theater', 'theatre', 'tiny_house', 'toilets', 'tower', 'townhall', 'trade_pavilion', 'train_station', 'university', 'utility', 'walkway', 'warehouse' and 'watch_house'.

After inspecting the OSM buildings layer, it became clear that some buildings were not classified in the ‘type’ category, preventing a comprehensive inclusion of all relevant buildings in the analysis. To assess the impact of these misclassifications on the final analysis results, the analysis was conducted twice. Firstly, without the OSM buildings layer entirely, and then a second time, including only correctly classified features of that layer. In this second run, the proportion of unclassified features and the buildings of interest was calculated.

After completing both analyses, a correction factor was determined based on the impact of the correctly classified buildings of interest on the overall results. This factor was then adjusted to account for the estimated impact of the misclassified buildings that might have been relevant gaps as described in Section 4.2.2.1.

The two layers were *clipped* to the 5km buffered basemap. To extract the settlements without including the buildings layer, the tool *extract by expression* was used on the OSM landuse layer maintaining the relevant categories. *Retain fields* was used to retain only the identifying fields, obtaining the “Settlements_3035_XXX” layer.

When including the OSM buildings layer, the *difference* tool was used with the raw layer and the “Settlements_3035_XXX” output to avoid including buildings that were already accounted for in the other layer. The *extract by expression* tool was used to retain only the relevant categories and the resulting layer was *merged* to the “Buildings_3035_XXX” layer. *Retain fields* was used once again, obtaining “Settlements2_3035_XXX”.

The operational radius and risk buffer were applied in a later stage, specified in section **Error! Reference source not found.** - **Error! Reference source not found.**.

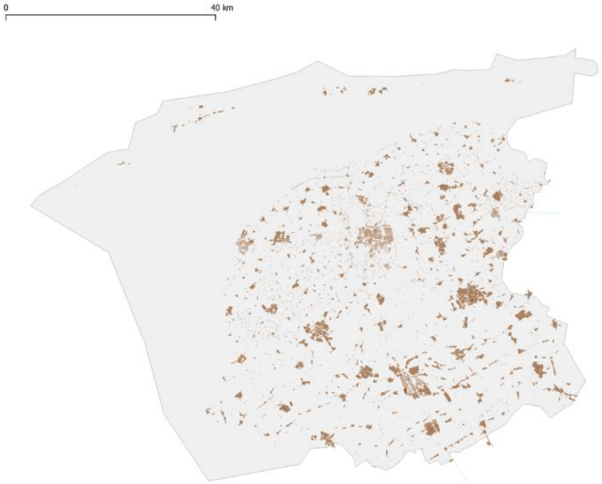


Figure 4.6. Settlements (shown in brown) including the ‘Buildings’ layer. Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL).

4.1.7 Military Areas

The requirement for this criterion was to avoid military areas and flying over these areas was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m.

The database used to obtain the relevant information was from OSM (2024) downloaded and accessed in September 2024 from (https://download.geofabrik.de/) - The layer on Land Use containing the category ‘Military’ was used.

The layer was *clipped* to the 5km-buffered basemap and the relevant category was extracted using the *extract by expression* tool in QGIS. The tool *retain fields* was applied to preserve only the features containing a unique identifier.

The operational radius was applied in a later stage, specified in section **Error! Reference source not found.** - **Error! Reference source not found.**.

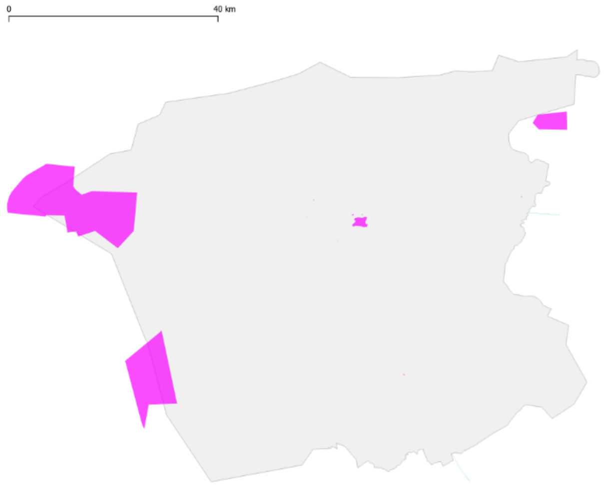


Figure 4.7. Military areas (shown in pink). Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL).

4.1.8 High Structures

The requirement for High Structures was to avoid them and leave a 100m safety buffer around them. Flying over these structures was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m.

Various categories were included under high structures for this analysis including: wind turbines, power cables and other towers (such as communication, observation and water towers). These layers were processed individually and then combined into a final 'high structures' layer.
The following sections go into further detail of processes applied to each of the layers included in the final high structures layer.

4.1.8.1 Wind Turbines

The dataset used for wind turbines was the "Windturbines - ashoogte" sourced from the Nationaal georegister accessed and downloaded from https://www.nationaalgeoregister.nl/

in September 2024. This dataset shows the location and hub height of all wind turbines in the Netherlands, and it was created by the Atlas Leefomgeving based on data from the RIVM, the BGT, Rijkswaterstaat, Openstreetmap and the External Safety Register (REV).

The dataset showed positional inaccuracies, with all points marking wind turbines being at least 75 meters off their correct locations. To address this issue, the Toggle Editing tool was used to apply the following adjustments to all features:

Distance (d): 74.439947 meters
Angle (a): -166.803035 degrees

After these corrections, some positions remained slightly misaligned (e.g., by approximately 7 meters), but the dataset was deemed sufficiently accurate for use in subsequent analyses.
The layer was *clipped* to the 5km-buffered basemap and the tool *retain fields* was used to preserve only the unique identifying features. A 50m *buffer* was also applied to account for the dimensions of the turbines.

4.1.8.2 Power lines / Power stations

The database used to collect data on power lines and power stations was OSM (2024). A line vector layer containing the locations of power cables in The Netherlands was used. OSM data was accessed and downloaded from the QuickOSM plugin in QGIS in September 2024. The key used for the search was “Power route/Power category” and was downloaded on a province level.
The layers were *clipped* to the 5km-buffered basemap and the tool *retain fields* was used to preserve only the unique identifying features. A 5m *buffer* was also applied to account for the width of the power lines.

The Power route layers extracted for each province with the QuickOSM plugin, was compared with the “power_towers” layer, also extracted from the QuickOSM plugin, and with satellite images. Only the “route” features classified as “power” were kept. A more thorough inspection was then conducted and some lines that were not marking overhead power cables were erased manually using the vertex tool. All the layers obtained from each province were merged and the duplicated features were erased. The new layer was saved and only the features ‘full_id’, ‘osm_id’, ‘osm_type’, ‘route’, ‘wires’, ‘voltage’, ‘operator_w’, ‘frequency’, ‘cables’ were saved.

The requirement applied to power cables was to avoid them and a 5m buffer was added to account for the width of the structure. The tool *retain fields* was used to preserve the identifying features and the resulting layer was *clipped* to the 5km buffered basemap.

4.1.8.3 Lighthouses and Other Towers

Two datasets were used to map lighthouses and other towers in The Netherlands:

- OSM Data (2024): The vector layer called Points containing the catergories ‘comms_tower’, and ‘windmill’, which was downloaded and accessed from (https://download.geofabrik.de/) in September 2024 was used.
- The dataset used for lighthouses was the “Vuurtorens” layer sourced from the Nationaal georegister accessed and downloaded from https://www.nationaalgeoregister.nl/ in September 2024. It contains the lighthouses location along the Dutch coast.

Both layers were *clipped* to the 5km-buffered basemap. The tool *extract by expression* was used on the OSM layer to extract the relevant categories and the tool *retain fields* was used on both datasets to preserve only the unique identifying features. The layers were merged and a 5m *buffer* was also applied to account for the width of the structures.

The output layers of Wind turbines, power cables, lighthouses and other towers were merged and a safety buffer of 100m was added.

The operational radius was applied in a later stage, specified in section **Error! Reference source not found.** - **Error! Reference source not found.**.

Figure 4.8. High structures (shown in black). Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL), ©Nationaal Georegister (CC BY 4.0).

4.1.9 Roads

The requirement applied to this criterion was to avoid roads and flying over these structures was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m scenarios. Additionally, a risk buffer of 100m is applied in the base case for this criterion (as part of publicly used infrastructure). Sensitivity analysis on the risk buffer includes 0, 50 and 150m buffers.

The data regarding roads was sourced from Open Street Map accessed in September 2024 from (https://download.geofabrik.de/) – The layer on roads containing the categories ‘motorway’,

'motorway_link', 'primary', 'Primary_link', 'residential', 'secondary', 'secondary_link', 'tertiary', 'tertiary_link', 'trunk', ' trunk_link' and 'unclassified' was used.

The layer was *clipped* to the 5km-buffered basemap. The tool *extract by expression* was used to extract the categories of interest from the layer. A *buffer* of 5m was applied to account for the width of the roads and the tool *retain fields* was used to preserve only the features containing identifiers.

The operational radius and risk buffer were applied in a later stage, specified in section 4.2.1 - Site Identification.

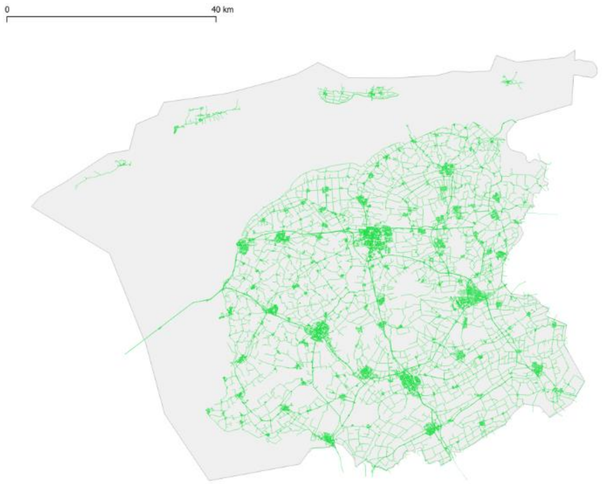


Figure 4.9. Roads (shown in green). Example: Friesland.
Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL), ©Nationaal Georegister (CC BY 4.0).

4.1.10 Railways

The requirement applied to this criterion was to avoid railways and flying over these structures was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m scenarios. Additionally, a risk buffer of 100m is applied in the base case for this criterion (as part of publicly used infrastructure). Sensitivity analysis on the risk buffer includes 0, 50 and 150m buffers.

The dataset used for railways was the "Vervoersnetwerken: Spoorwegen - Transport Networks: Rail (INSPIRE geharmoniseerd)" sourced from the Nationaal georegister accessed and downloaded from https://www.nationaalgeoregister.nl/ in September 2024. The Land Registry produces and manages the rail theme layer, which is unified and packed with pertinent items from TOP10NL (a component of the Basic Topography Registration BRT).

The layer was *clipped* to the 5km buffered basemap and the tool *retain fields* was used to preserve only the features containing identifiers.

The operational radius and risk buffer were applied in a later stage, specified in section **Error! Reference source not found.** - **Error! Reference source not found.**.

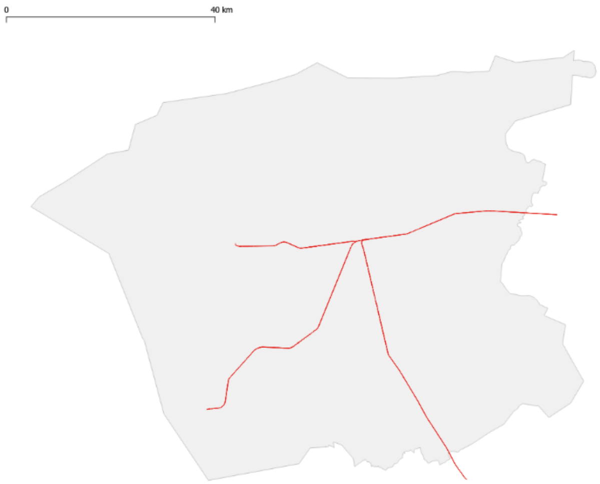


Figure 4.10. Railways (shown in red). Example: Friesland.

Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL), ©Nationaal Georegister (CC BY 4.0).

4.1.11 Air Traffic Areas

The requirement for this criterion was to avoid airspace restricted areas and flying over these areas was not permitted. A 425m operational radius buffer was applied as the base case. Sensitivity analysis on the operational radius includes 300, 650, 850 and 1050m scenarios. Additionally, a 5000m buffer was applied around airports and 1760m buffer was applied around airfields following the methodology implemented in Germany.

4.1.11.1 Restricted Areas

The data used for restricted airspace came from the Luchtverkeersleiding Nederland (LVNL), also known as Air Traffic Control the Netherlands, the organisation responsible for managing civil air traffic control in Dutch airspace. It was accessed through this website https://vfrchart.lvnl.nl/ an in September 2024. Maps containing Control Zones (CTR) were georeferenced into a single layer.

The layer was *clipped* to the 5km buffered basemap.

4.1.11.2 Airfields

Two datasets were used:

- OSM, downloaded and accessed in September 2024 from (https://download.geofabrik.de/). The Transport layer containing the category ‘helipad’ was used.
- The dataset “Vervoersnetwerken: Luchttransport - Transport Networks: Air (INSPIRE geharmoniseerd)” sourced from the Nationaal georegister accessed and downloaded from https://www.nationaalgeoregister.nl/ in September 2024. The Land Registry produces and oversees this layer, which is harmonised and packed with pertinent items from TOP10NL (a component of the Basic Topography Registration BRT). Three layers were included in the dataset, and only the layers “AerodromeArea” and “RunwayArea” were used.

Both layers from the NGR were *merged* into a single layer and the features that were outside the CTR areas (from the layer processed in the previous section 4.1.11.1), were extracted using the *extract by location* tool. The resulting layer was *clipped* to the 5km buffer basemap. The OSM layer was also *clipped* to the buffered basemap, and the tool *Extract by Expression* was used to extract the relevant category (heliports). The two layers were then *merged* and a 1760m *buffer* was applied to the output.

To obtain the final Air Traffic layer, the resulting layers from the Airfields and the Restricted areas were *merged* and the *retain fields* tool was used to maintain only the identifying fields.

The operational radius was applied in a later stage, specified in section **Error! Reference source not found.** - **Error! Reference source not found.**.

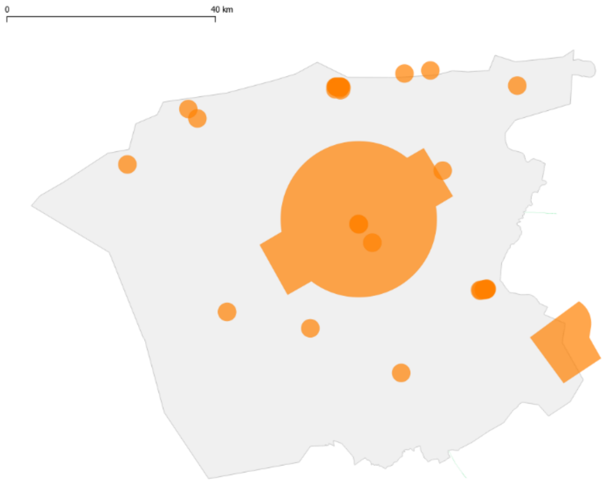


Figure 4.11. Air Traffic (shown in orange). Example: Friesland.

Source Data: GIS Data Mapog (freely available), ©OpenStreetMap Contributors (ODbL), ©Nationaal Georegister (CC BY 4.0), Luchtverkeersleiding Nederland (LVNL, freely available).

4.2 Data Processing

4.2.1 Site Identification

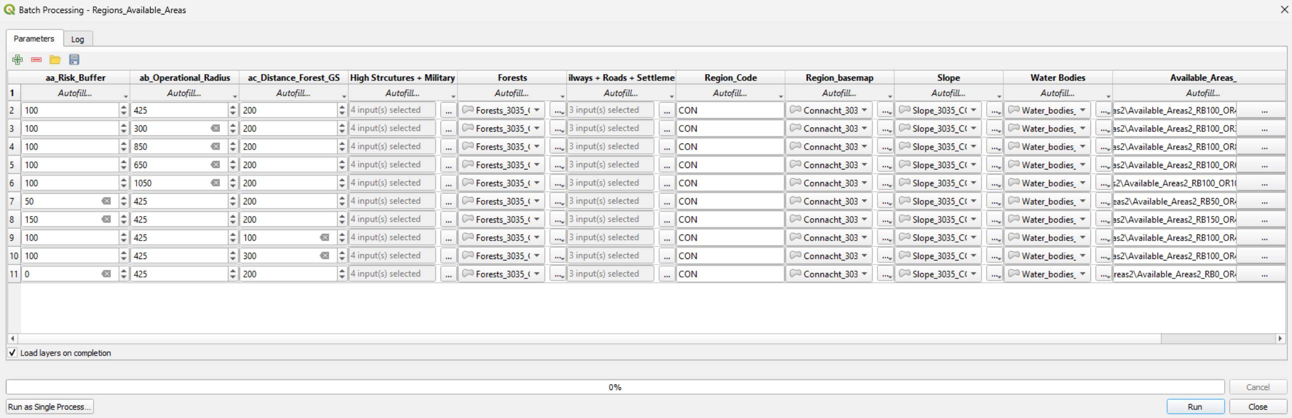
For the site identification process, new QGIS projects were created for the twelve Dutch provinces, and the analysis was applied individually to each region. The results were eventually integrated to generate final maps including information for the whole country.

A model was constructed in the Graphical Modeller to incorporate various parameters and conduct sensitivity analysis on the criteria. All the input layers consisted of the layers obtained through the Data Collection and Extraction procedure (See section **Error! Reference source not found.**).

1. Railways, Roads and Settlements layers were *merged*.
2. A risk *buffer* was applied to the merged layer from step 1. The magnitude of this "Risk Buffer" varied according to the applied scenario (0m, 50m, 100m, or 150m), using 100m as the base case.
3. Protected Areas, Military Areas, High Structures and Air Traffic layers were also *merged* into a single layer.
4. The outputs from steps 1 and 2 were *merged*.
5. Output from step 4 was subjected to an "Operational Radius" *buffer*. The size of the operational area buffer depended on the applied scenario (300m, 650m, 850m, or 1050m), using 425m as the base case.
6. Water Bodies were given a 100m *buffer*.
7. A *buffer* to determine the distance from the GS to forests was applied to the Forests layer. The scenarios explored were 100, 200 and 300m, using 200m as the base case.
8. Outputs from steps 3, 4 and 5 were *merged* into one single layer.
9. The *difference* tool was used using the output from step 6 and the Slope layer.
10. The resulting layer from step 7 was *clipped* to the base map layer from the corresponding region.

11. The tool *multiparts to singleparts* was applied to the output layer from the previous step and the output layer was saved.

Thanks to the *batch processing* tool, it was possible to iterate the analysis applying the different sensitivity analysis on the layers (See Figure 4.12). Moreover, all the batch process inputs were saved as .json files to allow validation and quality control.



	aa_Risk_Buffer	ab_Operational_Radius	ac_Distance_Forest_GS	High Strcutures + Military	Forests	ilways + Roads + Settleme	Region_Code	Region_basemap	Slope	Water Bodies	Available_Areas_
1	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...	Autofill...
2	100	425	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB100_OR
3	100	300	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB100_OR
4	100	850	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB100_OR
5	100	650	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB100_OR
6	100	1050	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	s2\Available_Areas2_RB100_OR1
7	50	425	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	eas2\Available_Areas2_RB50_OR
8	150	425	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB150_OR
9	100	425	100	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB100_OR
10	100	425	300	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	as2\Available_Areas2_RB100_OR
11	0	425	200	4 input(s) selected	Forests_3035_	3 input(s) selected	CON	Connacht_303	Slope_3035_C	Water_bodies_	reas2\Available_Areas2_RB0_OR

☑ Load layers on completion

Figure 4.12. Image showing example of the batch processing for the site identification analysis.

The final deployment area layers for each region (see Figure 4.13) were saved with a systematic name that would allow the identification of each scenario: "Deployment_Areas_RBxxx_ORxxx_Fxxx_3035_XXX".

RBxxx = 'RB' stands for Risk Buffer and xxx for the number indicating the scenario applied.

ORxxx = 'OR' stands for Operational Radius and xxx for a number indicating the sensitivity analysis applied.

Fxxx = 'F' stands for Forest and xxx for the number indicating the sensitivity analysis applied (distance from forests to the GS).

3035 = indicates the projection.

XXX = Indicates the region code.

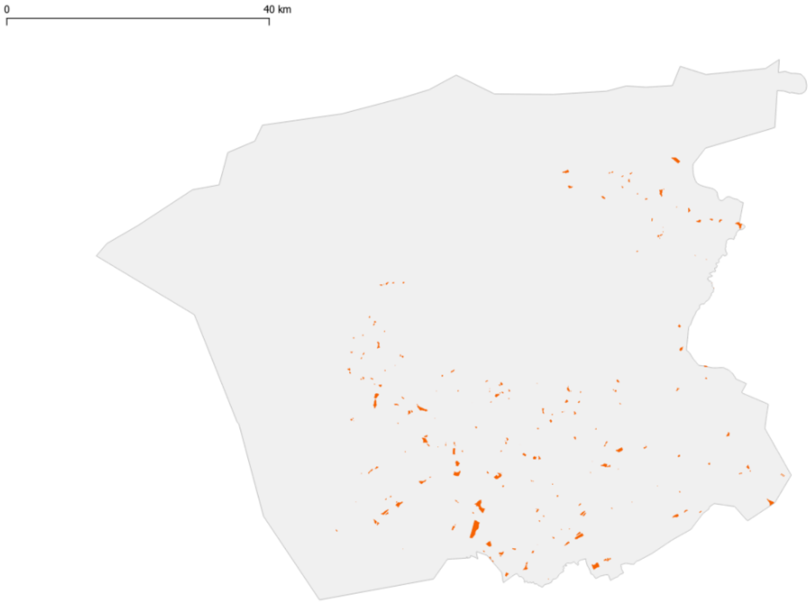


Figure 4.13. Ground Station Deployment Areas (in orange) using the base case scenario. **Example: Friesland.**

Source Data: GIS Data Mapog (freely available), ©NASA Shuttle Radar Topography Mission (NASA JPL), ©OpenStreetMap Contributors (ODbL), ©Copernicus (CC BY 4.0), ©World Database on Protected Areas (WDPA, CC BY 4.0), UNESCO (freely available), ©Nationaal Georegister (CC BY 4.0), Luchtverkeersleiding Nederland (LVNL, freely available).

To obtain the final available sites for AWE deployment and operation at a national level (see example in figure Figure 4.14), one QGIS project was created for each scenario (ten in total), and all the Deployment Areas layers that were generated by region were merged following the next steps:

1. *Merge* all the layers in the project.
2. *Dissolve* the merged layers.
3. Add *auto incremental field* to have a unique identifier for each feature.
4. *Retain* only the field that was created in step 3.
5. Add *geometry attributes* (area and perimeter).
6. *Extract* only the features with Area ≥ 700m^2 (See section **Error! Reference source not found.**).
7. Add the Operational Radius *Buffer* specific to each scenario with "dissolve result" activated.
8. Apply the *Multipart to Singlepart* tool.
9. Repeat steps 3 to 5.

10. Export the outputs of step 6 (Deployment Areas) and 9 (Operational Areas), both in shapefile and spreadsheet format.

Both the 'Deployment areas' and 'Operational Areas' layers were named with the same systematic name as explained above.

Figure 4.14. Ground Station Deployment Areas and Operational Areas (in orange) in The Netherlands using the base case scenario requirements.

Source Data: GIS Data Mapog (freely available), ©NASA Shuttle Radar Topography Mission (NASA JPL), ©OpenStreetMap

Contributors (ODbL), ©Copernicus (CC BY 4.0), ©World Database on Protected Areas (WDPA, CC BY 4.0), UNESCO (freely available), ©Nationaal Georegister (CC BY 4.0), Luchtverkeersleiding Nederland (LVNL, freely available).

4.2.2 Capacity calculation

To support the calculation of the technology's capacity in The Netherlands, the spreadsheet data detailing the area of deployment and operational were utilised. The total available area for AWE GS deployment, the overall operational area, the number of deployment sites, and the capacity of these sites were calculated.

Following the methodology developed for the analysis in Germany, a triangulation method was employed to estimate the maximum number of devices or GS that could be efficiently installed within each designated deployment area.

This triangulation method assumes that the optimum layout for maximising the number of objects (total number >3) within a given area is to place objects in a triangular pattern. In order to apply this method, it is necessary to define the minimum separation distance between objects and the footprint of individual object (i.e., the ground station). In this case the footprint of the ground station was taken as 30m while the minimum separation distance was taken to be 400m.

For N devices > 3 the minimum area required was found to follow a straight line ($R^2 = 0.9992$)

The trendline equation obtained was:

$$y = 157{,}151x - 472{,}874$$

where y = minimum area and x = the number of devices.

Note: The triangulation method is a simple technique to estimate the number of devices for a large number of identified sites in an automatic way where the number of sites is too great to define manually or to run layout optimisation techniques. This method works best for sites which are regular in shape and is less accurate for long, elongated or irregular shapes. However, at this scale it seems to give a good first estimate of the number of devices.

In order to estimate the number of devices that could be hosted within the identified areas, specific criteria were applied. Areas ranging from 700m^2 to 13,800m^2 were determined suitable for hosting one device[11], while areas ranging from 13,800m^2 to 91,540m^2 could host up to two devices. For areas larger than 91,540m^2, the trendline equation was utilized to calculate the maximum number of devices that could be supported.

To ensure practicality and realism in the estimation process, all calculated numbers on the number of devices were rounded down to obtain whole numbers. This approach provides a more precise and realistic estimation of the actual number of devices that could be hosted within each respective area.

Once the total number of devices was determined, a direct calculation was conducted to ascertain the potential capacity of the AWE system. This calculation was based on a straightforward conversion rate of either 200 kW or 1.5 MW per device, allowing for a comprehensive assessment of the potential capacity range which is technology specific. The former rate provided a conservative estimate, while the latter yielded a more optimistic estimation, considering power generation capability of different technologies and devices (See results in Section **Error! Reference source not found.**).

4.2.2.1 Correcting factor

As previously introduced in Section **Error! Reference source not found.** - **Error! Reference source not found.**, it was necessary to run the model twice to be able to verify the accuracy of the building-

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[11] Areas smaller than 700m^2 (minimum area for a ground station with 30m diameter footprint) were discarded. The shape of certain polygons could have led to overestimation in total deployment area, as the threshold for discarding areas smaller than 700m^2 may not account for elongated or irregular shapes that meet the minimum required area but that cannot accommodate a 30m diameter device. Developers with smaller diameter requirements may still consider these areas for potential use.

related analysis in the study. A key issue in the OSM buildings dataset was identified. Approximately 40% of the buildings were listed as NULL in the "type" category, meaning that no information was available regarding the type of building. This lack of classification prevented a comprehensive inclusion of all relevant building types in the analysis. For the purpose of this study, relevant buildings were defined as houses, industrial buildings, other inhabited buildings, or public/commercial buildings, while farming-related structures were ignored in the analysis.

To assess the impact of these NULL values on our results, the analysis was first conducted without using the OSM buildings layer, relying instead on other available layers that provided less complete settlement information. This provided a baseline result for comparison.

In a second run, the analysis was performed using only the buildings that had a valid classification in the "type" category. The unclassified (NULL) buildings were excluded entirely from this run. Of the classified buildings, 90% were identified as relevant (i.e., of the 60% of buildings with valid classification, 90% met the criteria for inclusion). This resulted in a value representing the impact of correctly classified buildings on the final results.

The next step was to calculate a correction factor to adjust for the exclusion of unclassified buildings. The simple ratio method was employed for this purpose. First, the results of the second analysis (with only correctly classified buildings) were compared with the results of the first analysis (without the buildings layer). The ratio was calculated using the formula:

$$Z = 1 - \left(\frac{Y}{X}\right)$$

Where:

Y is the result from the second analysis (with only classified buildings).

X is the result from the first analysis (without any building data).

This ratio (z) was then used to calculate the correction factor, which adjusts for the impact of misclassified (NULL) buildings. The correction was made using the following formula:

$$Corrected\ Results = \left(1 - \left(\frac{Z}{31.34\ x\ 90.27}\right)\right) x\ X$$

Where:

31.34 is the total percentage of classified buildings that were of interest (houses, industry, inhabited buildings, etc.).

90.27 is the percentage of classified buildings that were relevant.

Since no additional layers or ground-truth data were available to validate the correction factor, it was assumed that the percentage of misclassified buildings (NULL values) that were relevant would be similar to the percentage of relevant classified buildings.

The corrected results were then presented as a range: one with the corrected values and one with the results from the second run, which excluded all unclassified buildings.

5 Quality Control

Quality control for the data extraction process was implemented by an independent team member who had not been previously involved in the data extraction. This person conducted a visual inspection of all the selected features in each layer of the datasets. At least 20 features in three different states from each dataset were randomly chosen and carefully cross-referenced with corresponding satellite images.

Through this validation procedure, we aimed to ascertain the consistency and accuracy of the extracted data. Any discrepancies or potential errors on the features selection identified during this inspection were promptly rectified through further investigation and refinement of the data selection process.

5.1 Data Extraction and Site Identification

Both the data extraction and the site identification models underwent a validation process that included comparisons with previous analyses conducted manually on two different Dutch Provinces. To establish the models' accuracy and efficacy, we leveraged a dataset of layers and identified sites that had been previously identified through manual analysis. These layers along with manually identified sites served as a gold standard or benchmark against which the model's performance was measured. The outcomes of the validation process were highly promising, as the model displayed a perfect correlation of 100% with the manually identified sites.

After successfully validating the models, and with the data extraction and site identification stages executed using models developed in the QGIS Graphical Modeller and batch process tools (See Figure 4.12), we were able to monitor and verify the input data for each batch process following the completion of the analysis. This served as a robust quality control mechanism.

Following the generation of output layers from the data extraction and site identification processes, an impartial team member conducted thorough cross-checks to ensure proper generation of each layer. Additionally, all saved batch processes were reloaded and meticulously examined to verify the accurate completion of input field information. This scrutiny of the outputs and inputs served to uphold the integrity and precision of the entire analysis.

After generating the final layers, an AWE developer cross-referenced certain locations previously identified during a site identification and selection exercise they conducted, noting a remarkably high correlation of suitable sites with this analysis.

6 Results

Following the completion of the site identification process, ten distinct scenarios were generated by considering variations in the risk buffer, operational radius, and distance from the GS to forests. These scenarios allow us to evaluate the impact of these criteria on the availability of areas that are suitable for installing AWE devices.

The results are both presented in Table 6.1 and in the maps presented below. The table showcases the outcomes derived from each scenario applied, allowing the recognition of the significant impact that arises from the use of different requirements.

The key results, i.e., GS Deployment Area, Number of Devices, Minimum Capacity and Maximum Capacity, from Table 6.1 have been visualised in Figure 6.1, Figure 6.2, Figure 6.3, and Figure 6.4 respectively.

Table 6.1. Results of the site identification analysis applying different scenarios. Base Case highlighted in orange.

Test Case	Outer Operational Area (km²)	GS Deployment Area (km²)	N° of Sites	N° of devices	Min Capacity* (MW)	Max Capacity** (MW)
Base Case†	590 - 1,270	35 - 115	650 – 1,240	1,290 – 2,810	260 – 560	1,930 – 4,210
0m Risk Buffer	1,560 – 2,640	120 - 260	1,640 – 2,550	3,390 – 5,890	680 – 1,180	5,080 – 8,840
50m Risk Buffer	960 – 1,840	70 - 170	1,040 – 1,800	2,040 – 4,090	410 - 820	3,060 – 6,130
150m Risk Buffer	370 - 880	20 - 70	420 - 870	740 – 1,910	150 – 380	1,110 – 2,870
300m Op. Radius	1,550 – 2,510	190 - 370	2,410 – 3,600	5,040 – 8,360	1,010 – 1,670	7,560 – 12,5440
650m Op. Radius	10 - 230	0 – 10	10 - 150	0 - 250	0 - 50	0 - 400
850m Op. Radius	0 - 50	0 - 1	0 – 20	0 – 30	0 - 5	0 – 50
1050m Op. Radius	0	0 - 0.001	0	0	0	0 – 1.5
100m Distance to forests	570 – 1,340	30 - 120	640 – 1,330	1,240 – 2,970	250 – 590	1,860 – 4,460
300m Distance to forests[12]	620 – 1,210	40 - 110	670 – 1,180	1,370 – 2,660	270 - 530	2,050 – 3,990

† Base case: Operational Radius 425m, 100m risk buffer and 200m distance to forests.

* Minimum capacity contemplates a capacity of 200 kW per device.

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[12] It does not seem correct that the 300m distance to forests has greater min operational area and GS dep. Area than the 100m distance to forests however no issues were found in QC for parameters used in regional model and the correct output files have been confirmed in the spreadsheet. This appears to be an artefact of the correction factor applied to account for the unclassified settlements. i.e. a stronger correction factor is applied for the 100m distance than the 300m distance.

** Maximum capacity contemplates a capacity of 1.5 MW per device

The results show there is a large variation in the number of potential sites in the Netherlands, ranging from 0 (850m and 1,050m OR) to 3,600 (300m OR) potentially suitable locations. The base case analysis (RB100, OR425, F200) identified between 590 and 1,270km^2 of outer operational area, and between 35 and 115km^2 of deployment area in the Netherlands suitable for potential AWE deployment. This base case area has the potential to support an estimated AWE capacity of up to 1.9 to 4.2GW (assuming an individual device capacity of 1.5MW). Among the scenarios evaluated, the most advantageous involved either reducing the operational radius to 300m or reducing the risk buffer to 0m. As a result, both these adjustments yielded similar results, with both giving an operational space of roughly 1,500 to 2,600km^2 suitable for AWE deployment, allowing for a greater number of devices with a potential capacity of between 1 to 12GW, contingent upon the capacity of each individual device.

Across the base case, the 0m risk buffer, the 50m risk buffer, the 150m risk buffer, and scenarios altering the distance to forests, a similar capacity per unit area is evident (ranging from 0.40 to 0.44MW/km^2 for 200 KW/device and 3.0 to 3.30 MW/km^2 for 1.5MW/device). Notably, the primary influencing factor on this metric is the tether length, i.e., operational radius. As can be seen in Figure 6.1, Figure 6.2, Figure 6.3, and Figure 6.4, the graphs of the risk buffer and distance to forests scenarios are broadly linear, with an inverse relationship between each parameter and distance, while the slope of the operational radius is curved, showing a steeper decrease in each parameter as the operational radius cases increase. The scenario featuring a 300m operational radius demonstrates a notably higher capacity per unit area (0.65MW/km^2 for 200kW/device and 4.87MW/km^2 for 1.5MW/device) compared to others, while the 1050m tether displays zero capacity per unit area of all scenarios analysed. These capacity per unit area results align with the findings for Ireland within the DEM-AWE project and power density capacity calculated in other studies on AWE Power Potential conducted by TU Delft within the JustWind4All project. These studies assumed a power density of 2MW/km2 for onshore AWE soft wing technology.

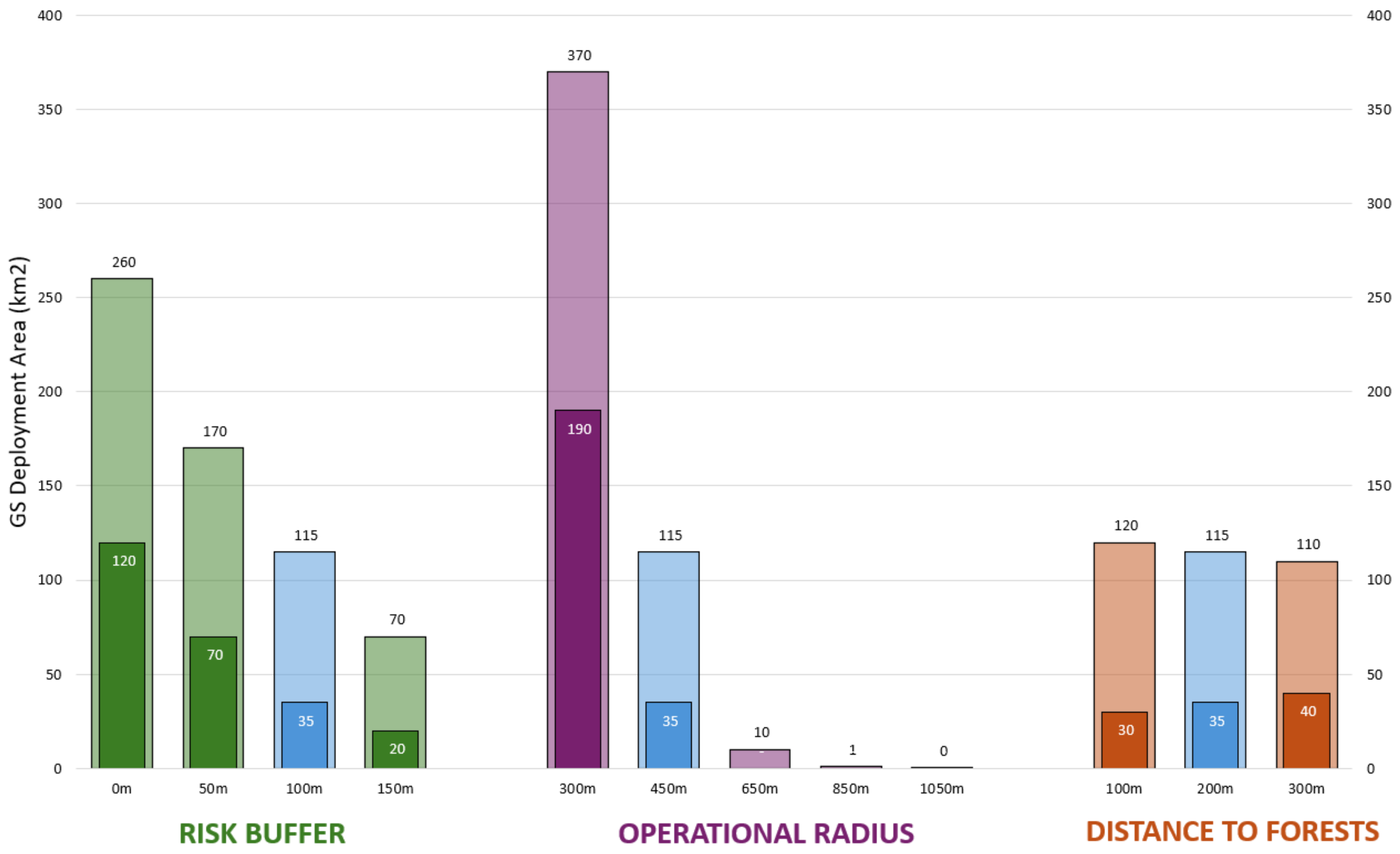

Figure 6.1. Total area (km^2) suitable for GS deployment in the scenarios studied. The results are grouped by modified parameters to assist with the visualization. To facilitate comparison, the base case (the blue bar) is present in the three groups. The wider, translucent bars represent the maximum value, while the narrower, solid-coloured bars represent the minimum value.

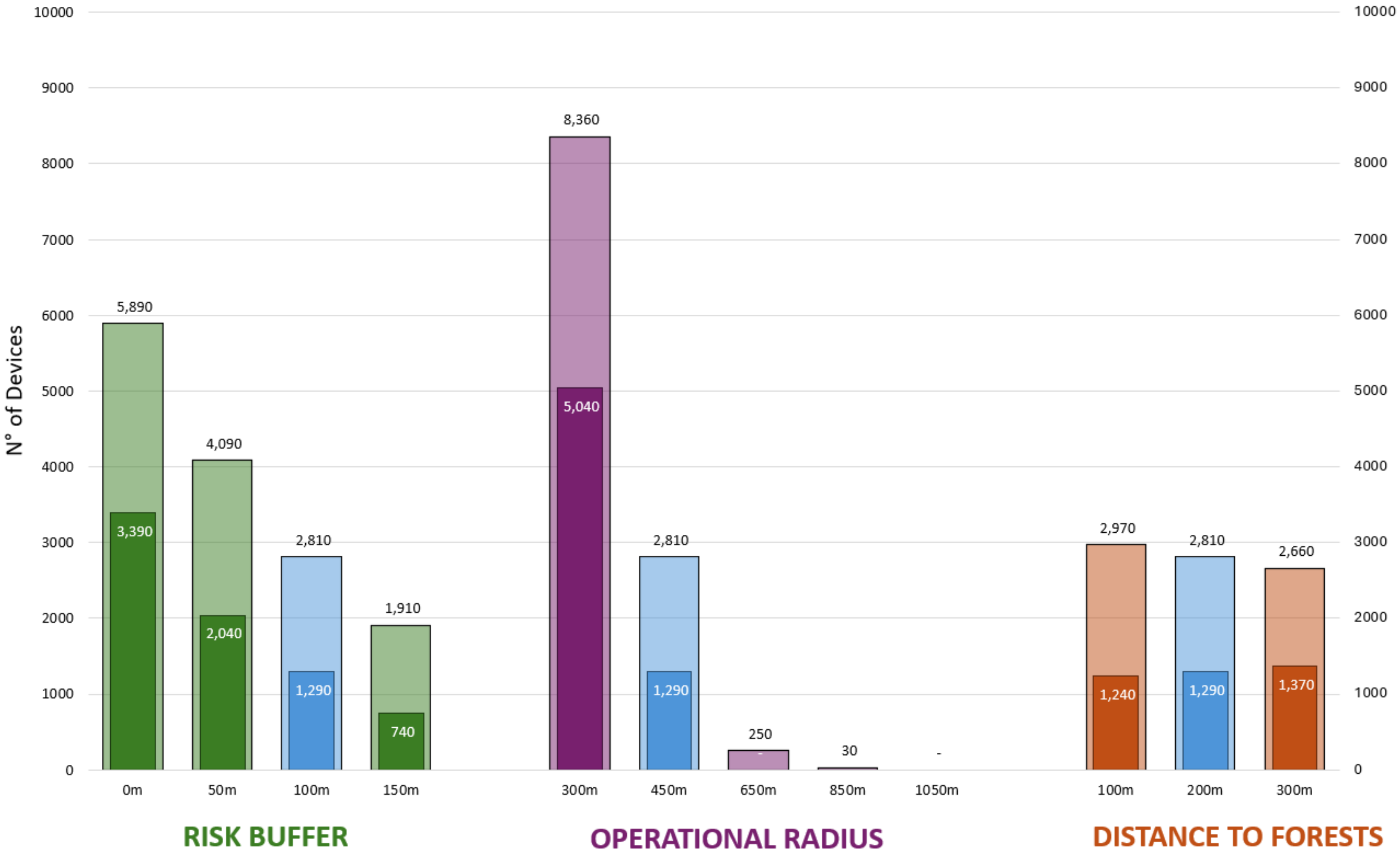

Figure 6.2. Total number of devices that can be deployed in each of the scenarios studied. The results are grouped by modified parameters to assist with the visualization. To facilitate comparison, the base case (the blue bar) is present in the three groups. The wider, translucent bars represent the maximum value, while the narrower, solid-coloured bars represent the minimum value.

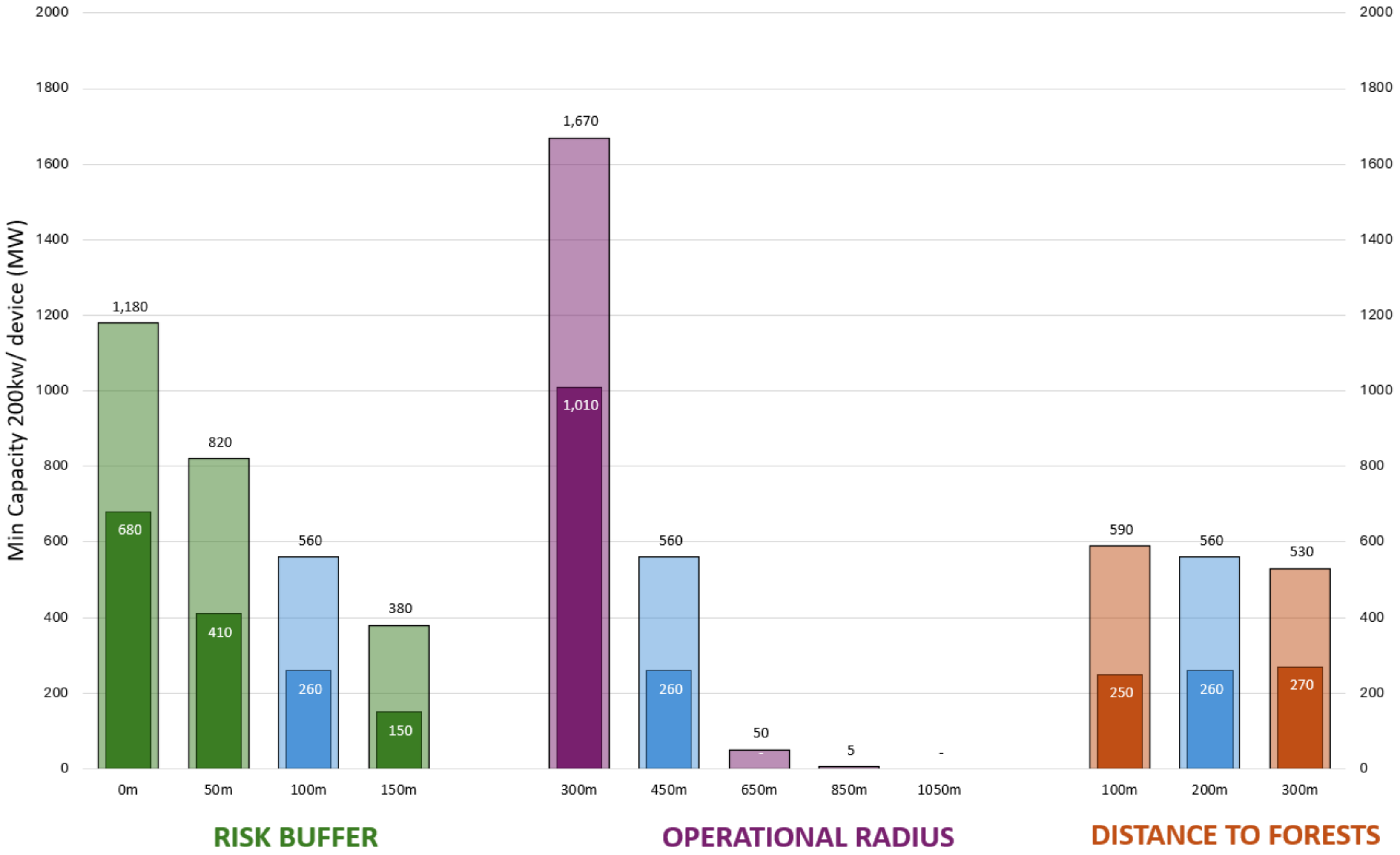

Figure 6.3. Capacity in MW that can be deployed in each of the scenarios studied (<u>based on devices with a 200kW capacity</u>). The results are grouped by modified parameters to assist with the visualization. To facilitate comparison, the base case (the blue bar) is present in the three groups. The wider, translucent bars represent the maximum value, while the narrower, solid-coloured bars represent the minimum value.

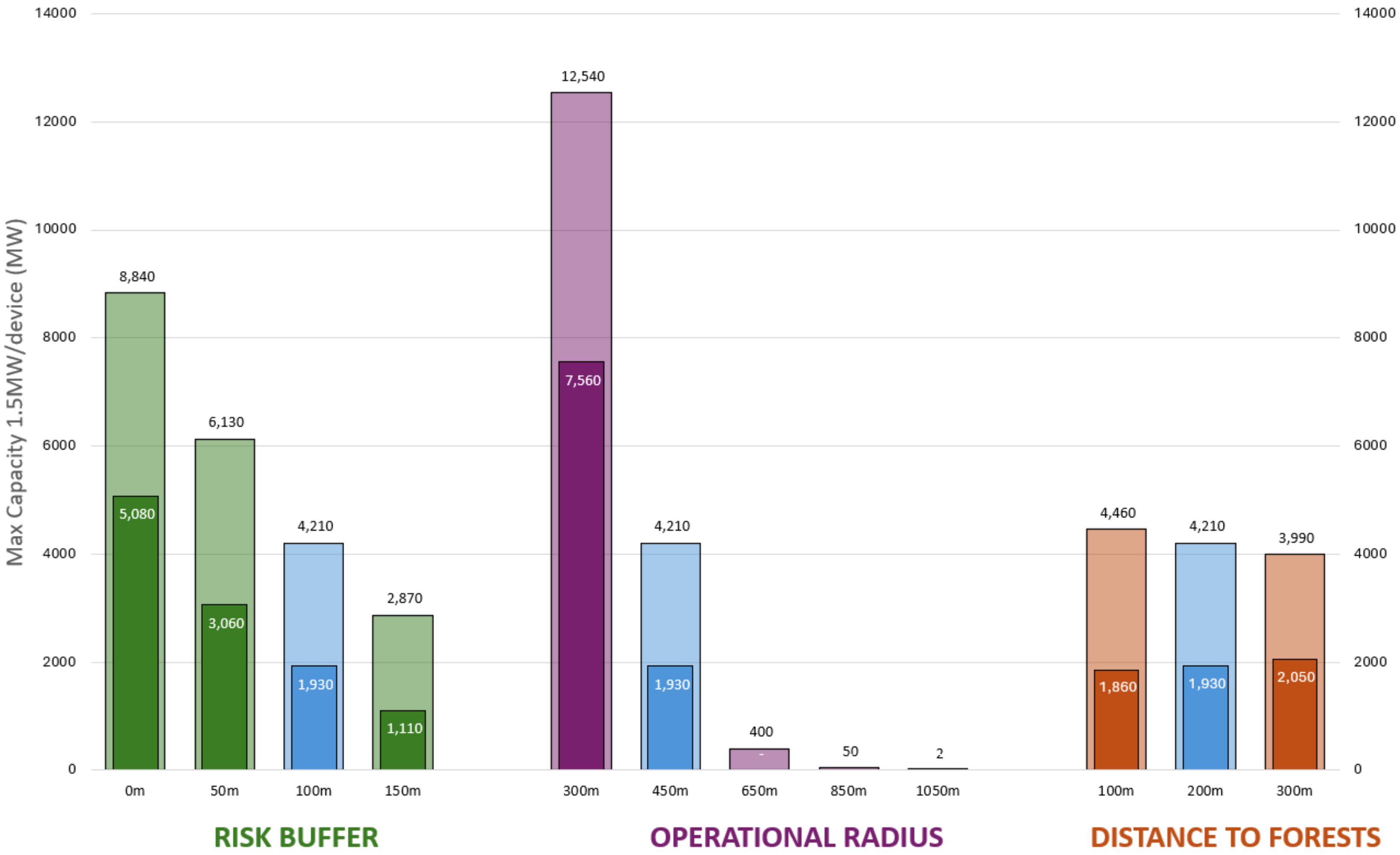

Figure 6.4. Capacity in MW that can be deployed in each of the scenarios studied (based on devices with a 1.5MW capacity). The results are grouped by modified parameters to assist with the visualization. To facilitate comparison, the base case (the blue bar) is present in the three groups. The wider, translucent bars represent the maximum value, while the narrower, solid-coloured bars represent the minimum value.

The maps showcasing the identified areas corresponding to each scenario are presented below:

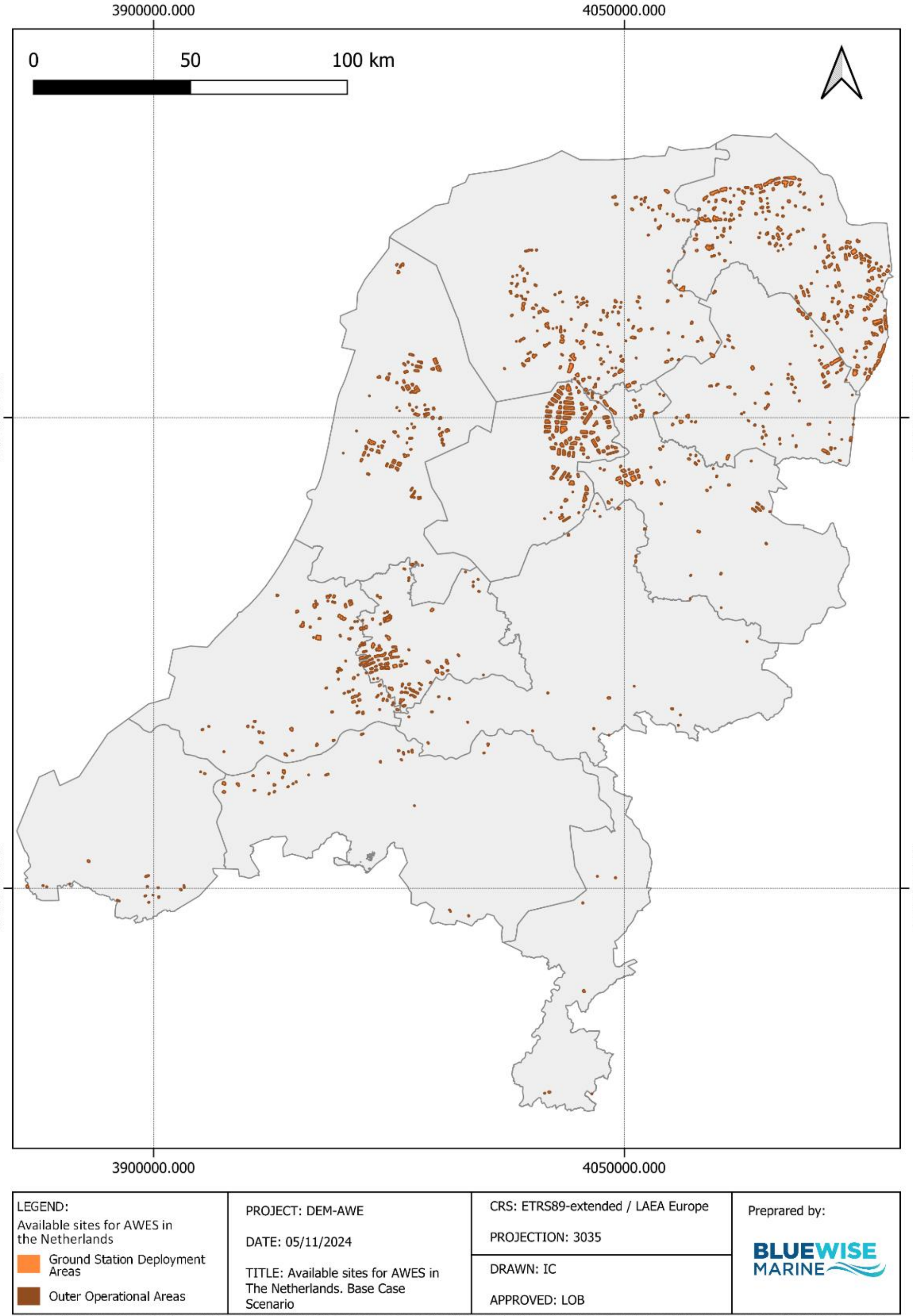

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Figure 6.5. Map showing suitable sites in the Netherlands after applying the base case scenario requirements.

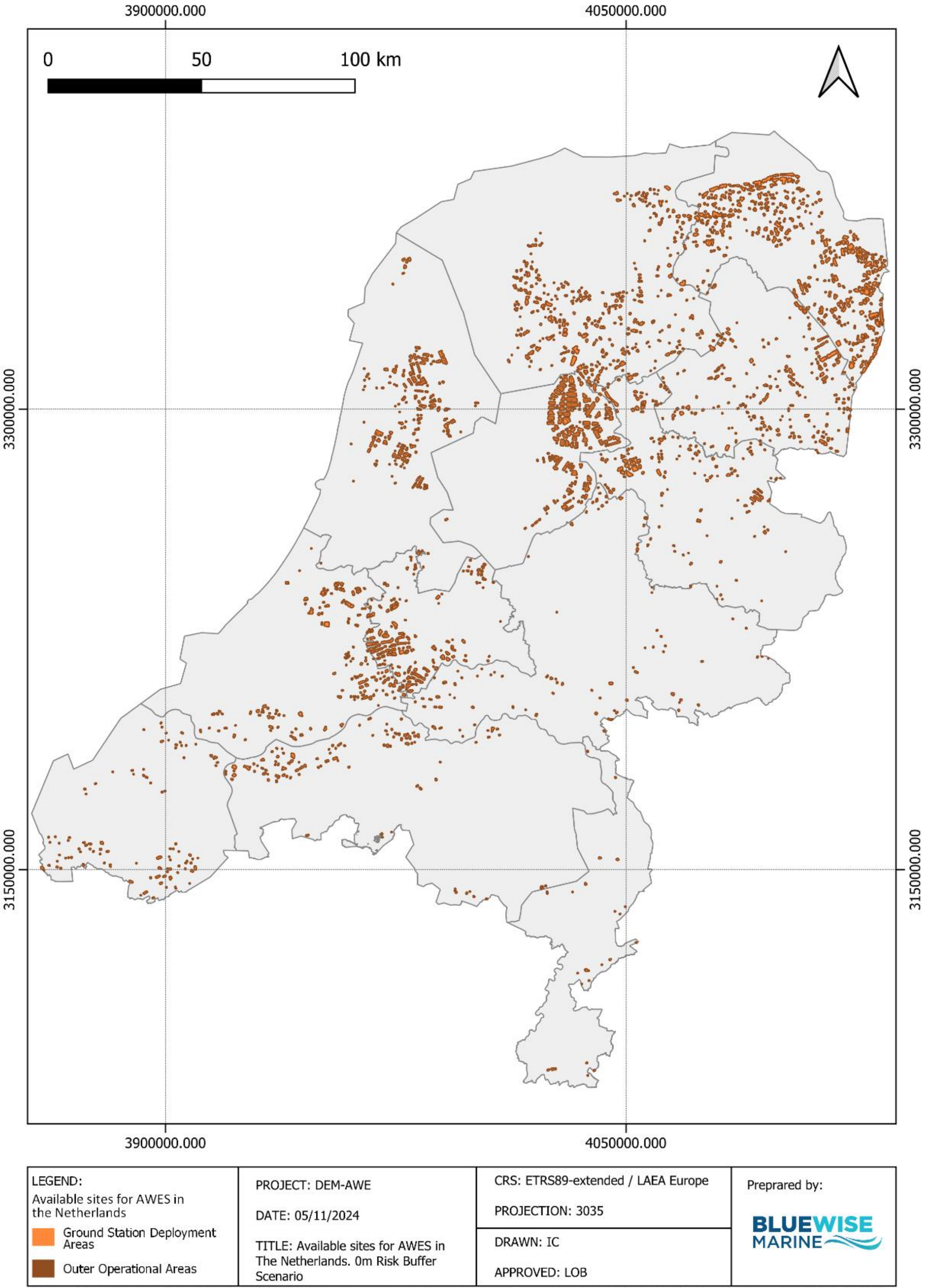

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Figure 6.6. Map showing suitable sites in Netherlands after applying the 0m Risk Buffer scenario requirements.

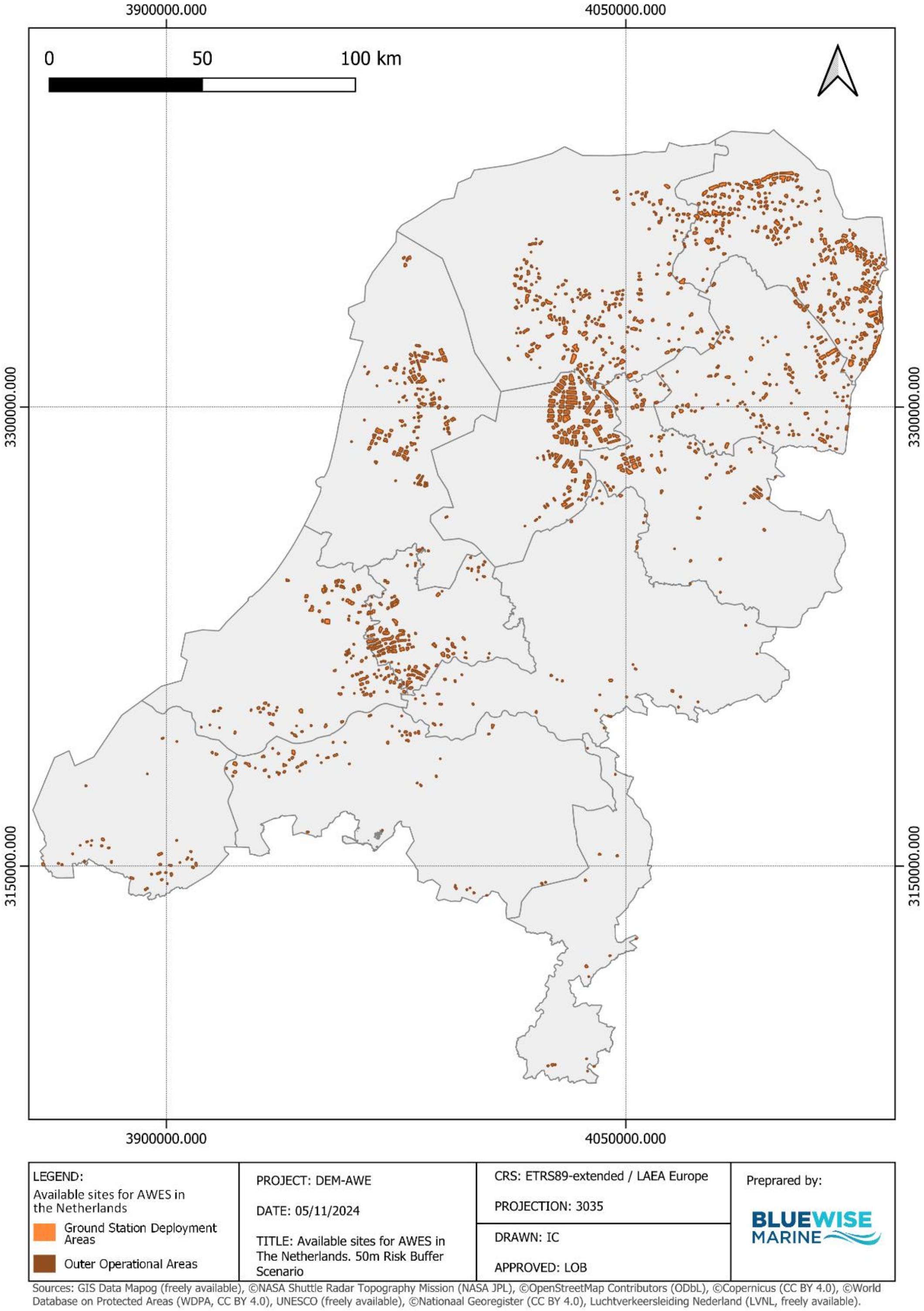

Figure 6.7. Map showing suitable sites in the Netherlands after applying the 50m Risk Buffer scenario requirements.

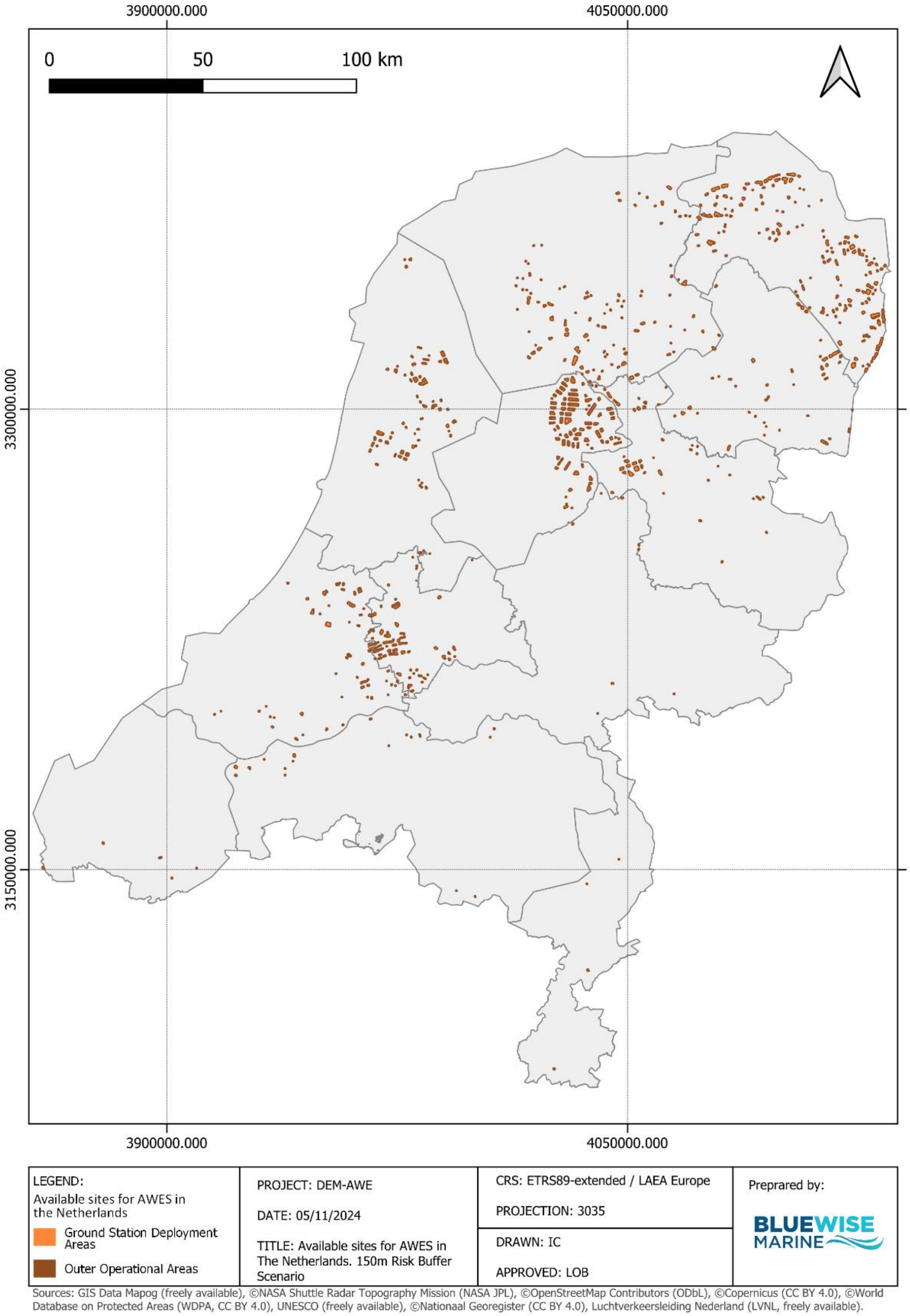

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Figure 6.8. Map showing suitable sites in the Netherlands after applying the 150m Risk Buffer scenario requirements.

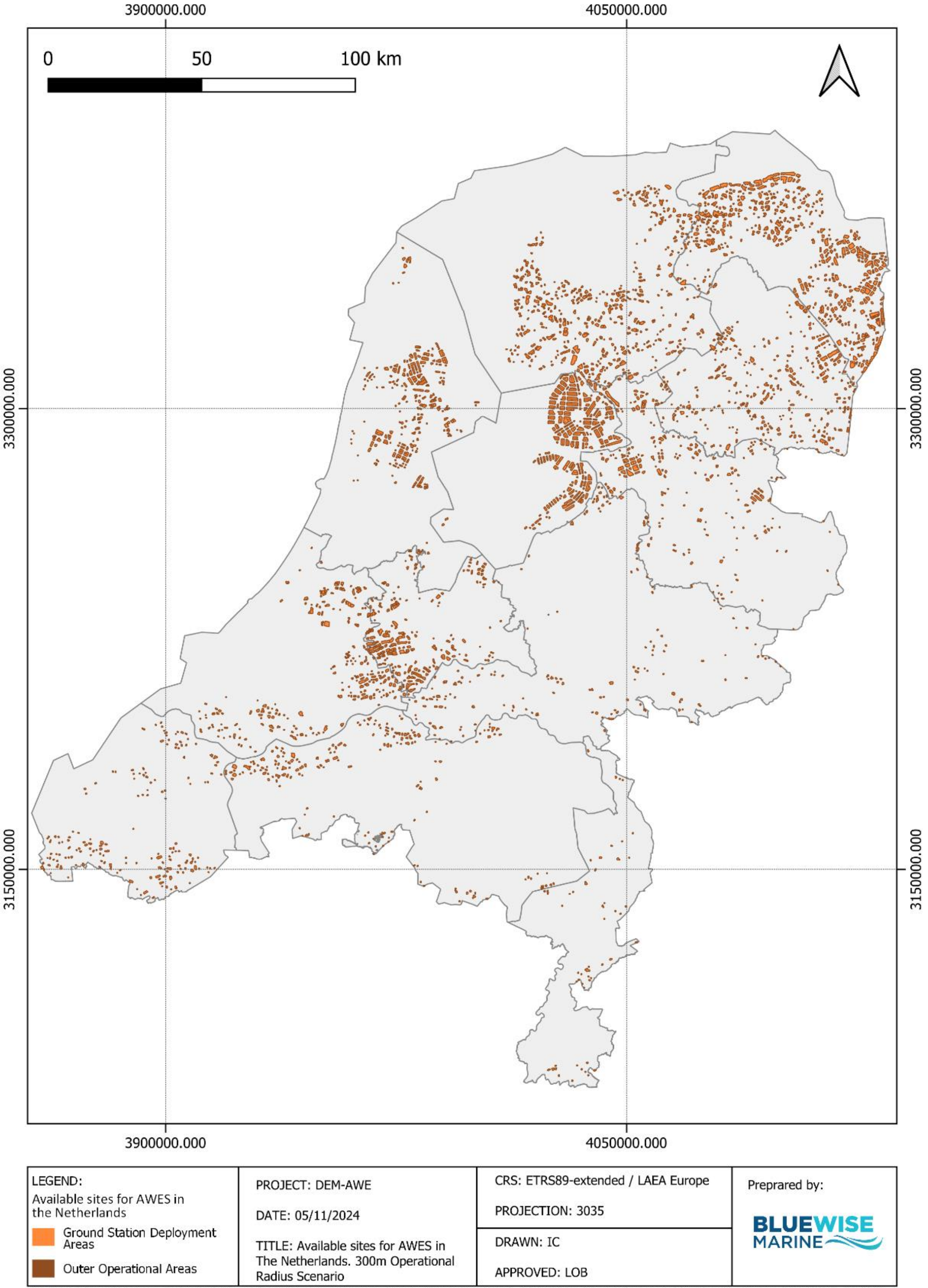

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Figure 6.9. Map showing suitable sites in the Netherlands after applying the 300m Operational Radius scenario requirements.

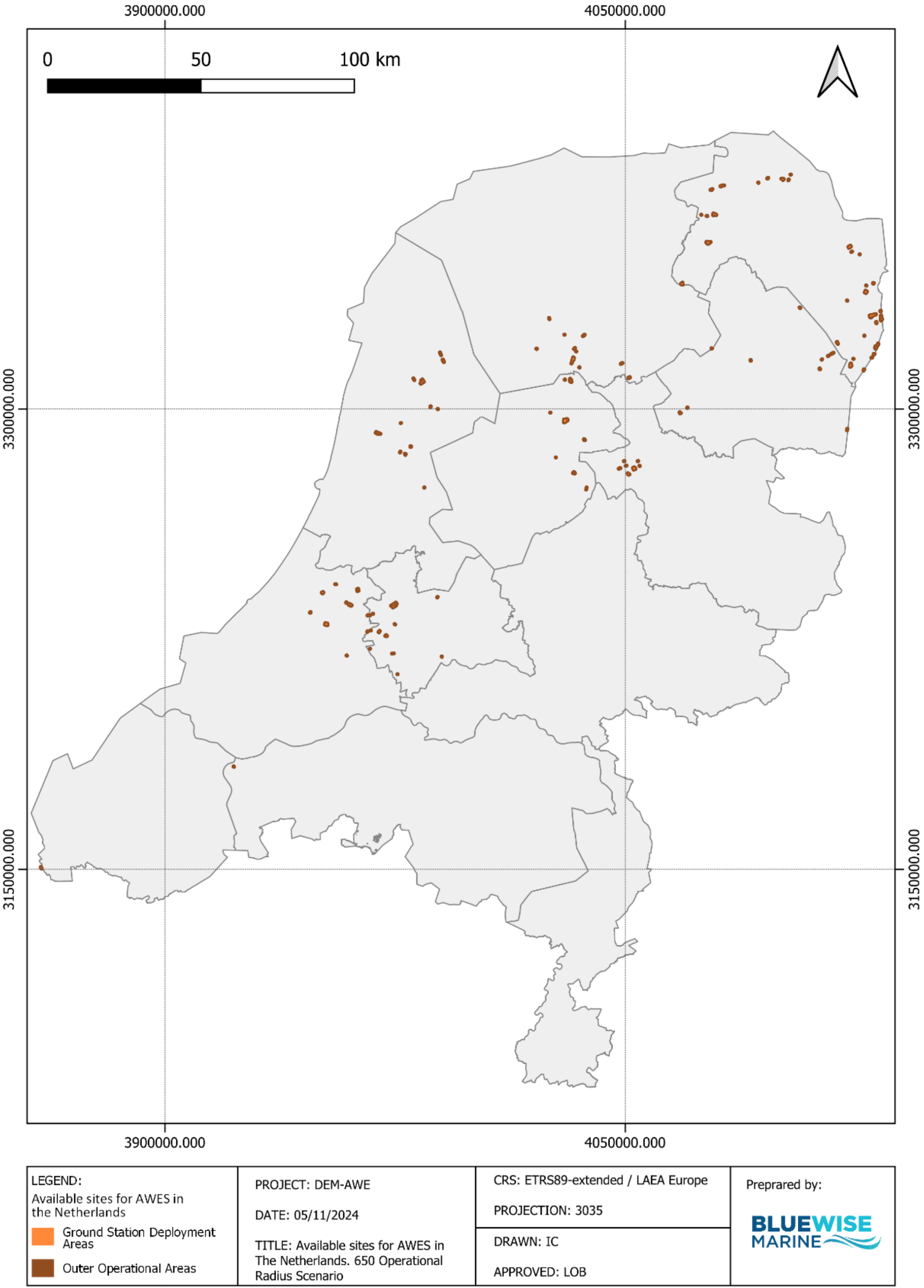

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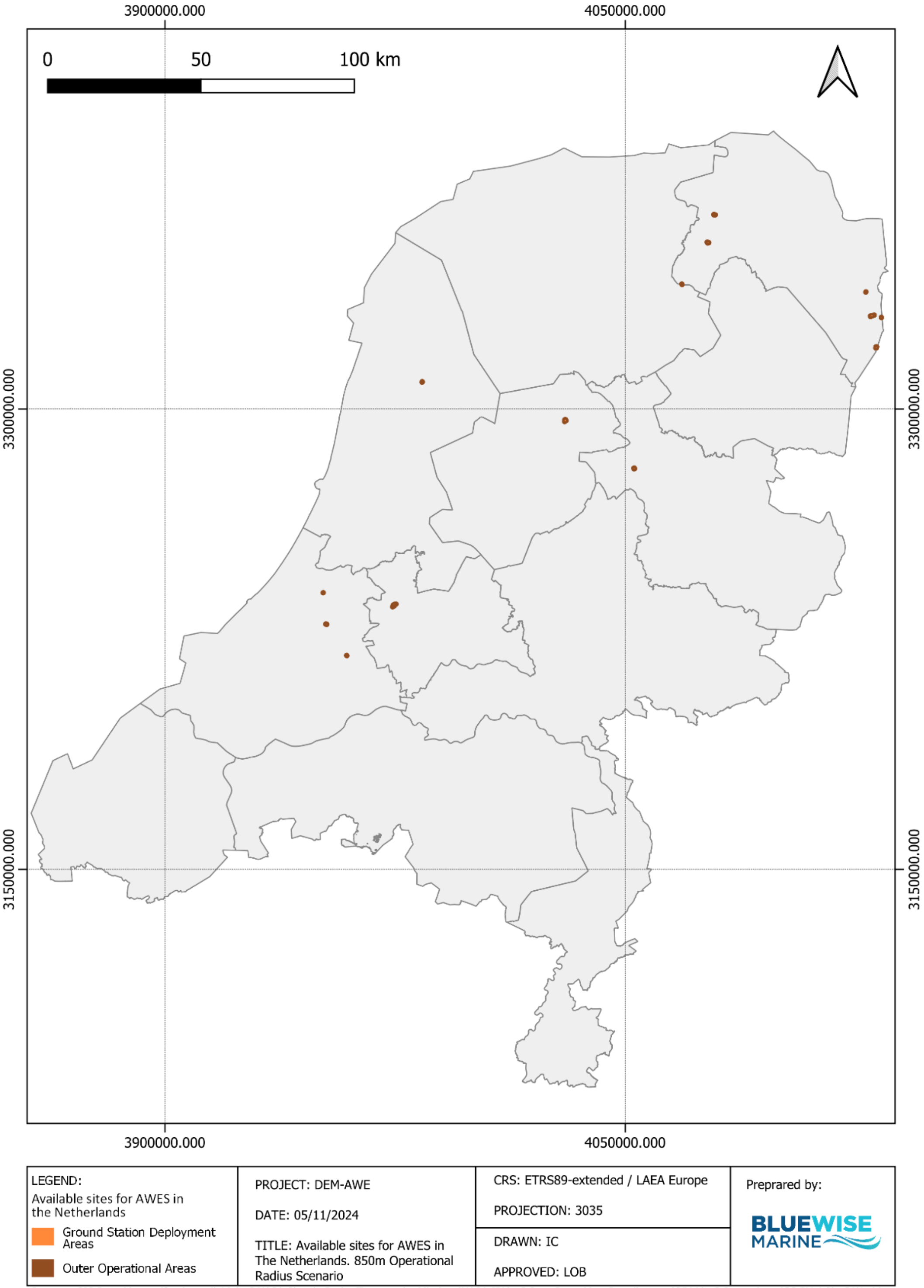
Figure 6.10. Map showing suitable sites in the Netherlands after applying the 650m Operational Radius scenario requirements.



LEGEND:
Available sites for AWES in the Netherlands
🟧 Ground Station Deployment Areas
🟫 Outer Operational Areas

PROJECT: DEM-AWE
DATE: 05/11/2024
TITLE: Available sites for AWES in The Netherlands. 850m Operational Radius Scenario

CRS: ETRS89-extended / LAEA Europe
PROJECTION: 3035
DRAWN: IC
APPROVED: LOB

Preprared by:
BLUEWISE MARINE

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Figure 6.11. Map showing suitable sites in the Netherlands after applying the 850m Operational Radius scenario requirements.

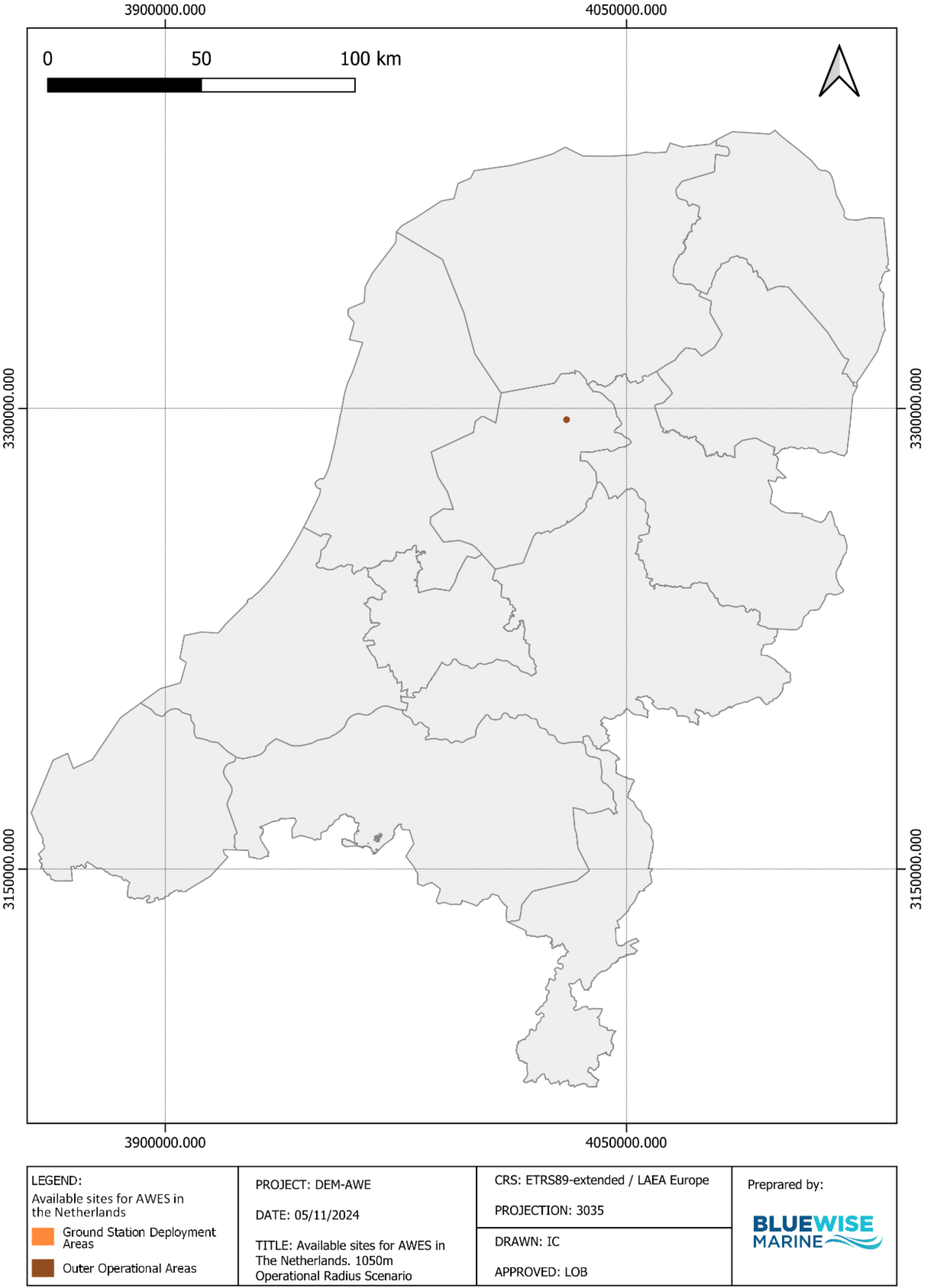

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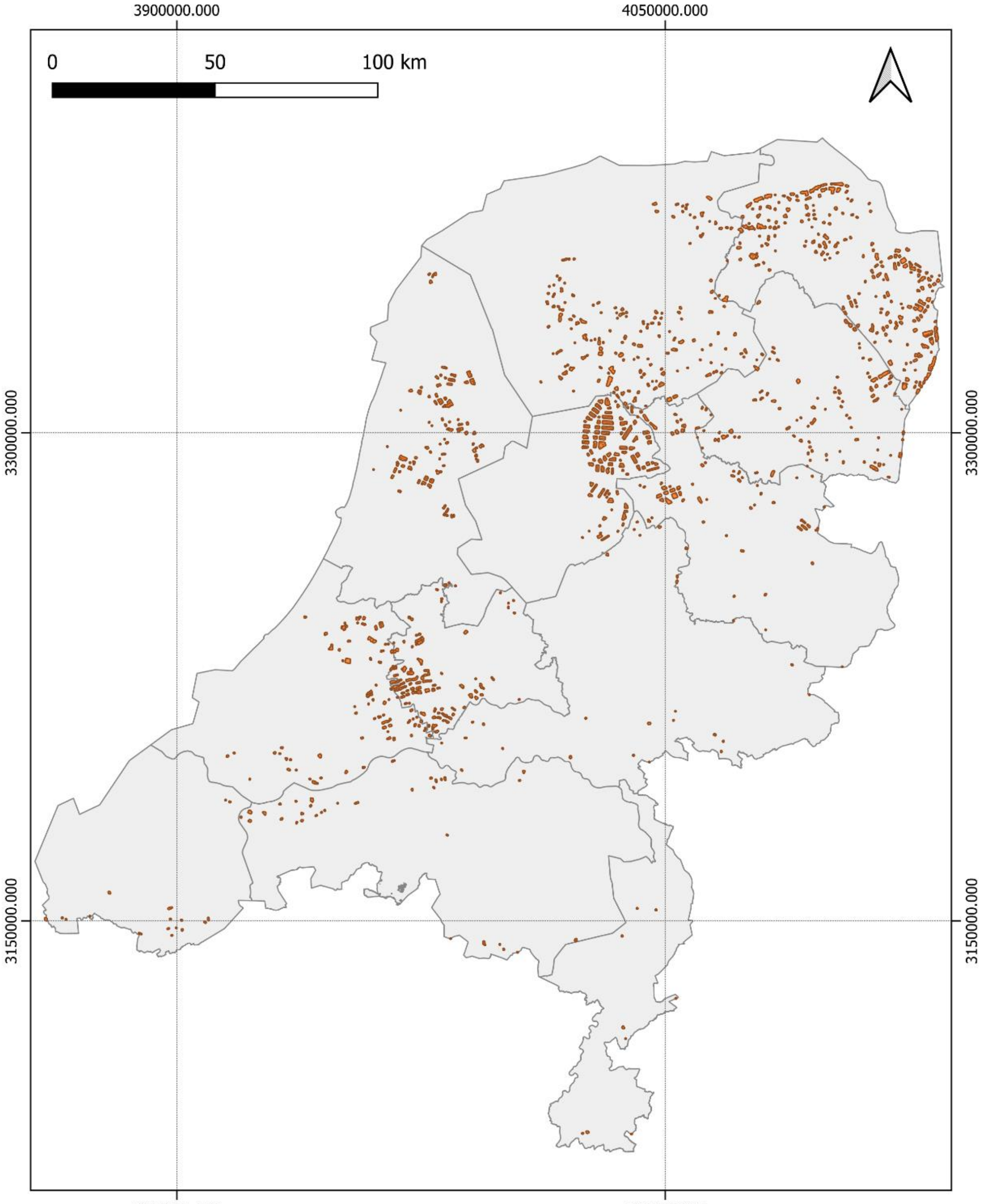
Figure 6.12. Map showing suitable sites in the Netherlands after applying the 1050m Operational Radius scenario requirements.



LEGEND: Available sites for AWES in the Netherlands 🟧 Ground Station Deployment Areas 🟫 Outer Operational Areas	PROJECT: DEM-AWE DATE: 05/11/2024 TITLE: Available sites for AWES in The Netherlands. 100m Distance to Forests Scenario	CRS: ETRS89-extended / LAEA Europe PROJECTION: 3035 DRAWN: IC APPROVED: LOB	Preprared by: BLUEWISE MARINE

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Figure 6.13. Map showing suitable sites in the Netherlands after applying the 100m from GS to forests scenario requirements.

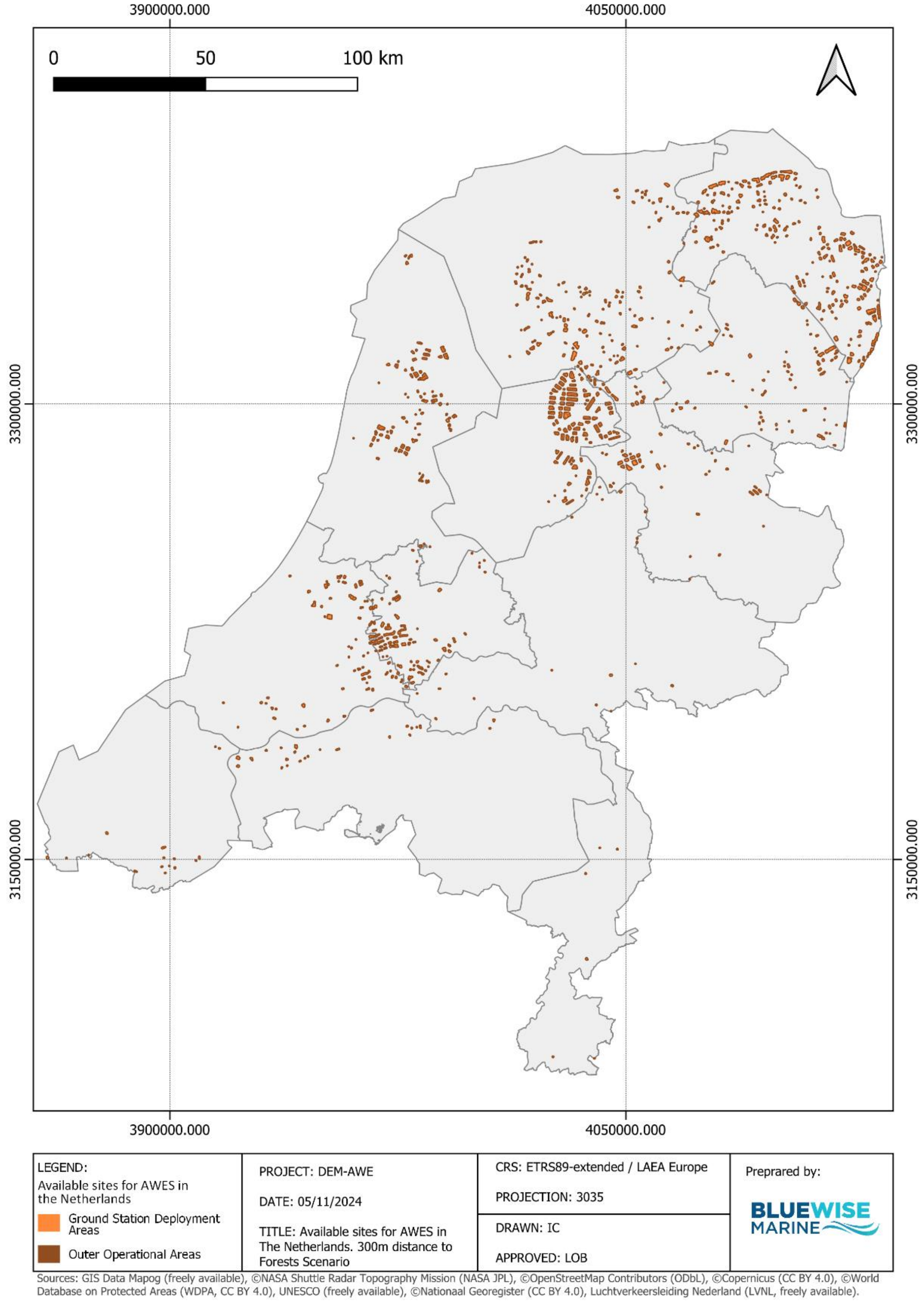

Figure 6.14. Map showing Suitable sites in the Netherlands after applying the 300m from GS to forests scenario requirements.

7 Summary

7.1 Main Insights

Based on the maps shown in Section 6 the Netherlands presents many areas which are potentially suitable for the deployment of AWE devices albeit the scale of the opportunity is largely dependent on the scenarios chosen. The highest density of potentially suitable areas appears to be in Friesland, Groningen and Flevoland regions to the North. These areas are characterised by extremely flat terrain (including areas of reclaimed land, mudflats and tidal areas) and tend to have a strong agricultural base including growing of crops and dairy production.

In contrast, Gelderland and Limburg in the southeast, which exhibit greater variation in elevation demonstrate less suitability for deployment of AWE technology.

Similarly, provinces to the west (e.g. Gelderland and Overijssel) have more diverse topography, including forests, rivers, and sandy areas which limits availability of land for AWE deployment, which is evident in the maps shown in Section 6.

The urbanised regions of Noord-Holland, Zuid-Holland, and Utrecht include with major cities like Amsterdam, Rotterdam, the Hague and Utrecht. These densely populated regions again demonstrate limited suitability for AWE technology however outside the cities e.g. on the borders between Zuid-Holland, and Utrecht there is some potential.

Relative to other countries, e.g. Germany (Coca-Tagarro, 2023) and Ireland, the potential for AWE technology in the Netherlands is less promising considering the country as a whole. The graphs and maps in Section 6 show the results of running the model with the different risk buffer, operational radius and distance to forests parameters. Overall, a lower proportion of the Netherland’s landmass is available as a potential AWE when compared to the previous study on Germany (Coca-Tagarro, 2023) and in Ireland. This may be in part due to the efficient land use and higher population density in the Netherlands at 544 people per square kilometre[13], compared to Ireland at 72.42[14] or Germany's 233 people per square kilometre[15].

The base case identified 590–1,270 km² of operational area and 35–115 km² of deployment area which translates to 650 – 1,240 sites and up to 2,810 devices, supporting 1.9–4.2 GW of AWE capacity.

Impact of operational radius: similarly to studies in other countries, the sensitivity analysis identified the operational radius as having the most substantial effect on the results. The operational radius is directly correlated to the tether length used by AWE developers. Adjusting the operational radius can lead to notable variations in the outcomes of the analysis, highlighting the need for careful consideration and optimisation of this parameter to ensure accurate and effective decision-making regarding GS deployment. As can be seen in Section 6, there is a much more significant reduction in the results of the model as the operational radius increases, especially when compared to the more linear reduction in the other parameters. It is important for developers to find the right balance between their technology's ideal operational requirements for exploiting high-altitude wind and the availability of suitable sites. They will need to carefully study and assess the trade-offs associated with different operational radius to optimise the deployment potential while considering factors such as wind resource availability, airspace constraints, and technological limitations. Striking the right balance ensures that AWE technology can effectively harness high-altitude wind resources while maximising the number of viable deployment sites.

Correction Factor: Due to time and data constraints, the correction factor was calculated based on the assumption that the percentage of buildings which were not classified is similar to that in the classified dataset. While this approach was the best feasible option, it introduces some potential caveats. The impact of unclassified buildings may differ from that of classified ones, and relying on

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[13] Netherlands Population (2025) - Worldometer

[14] https://www.macrotrends.net/global-metrics/countries/IRL/ireland/population-density)

[15] https://eurydice.eacea.ec.europa.eu/national-education-systems/germany/population-demographic-situation-languages-and-religions

this assumption could lead to over or underestimation. For instance, the model does not account for potential variations in the data such as unclassified buildings having a different proportion of relevant and irrelevant types, unclassified buildings could be more concentrated in certain areas, or vary in size and scale, and there was no sensitivity analysis performed due to lack of alternative data sources. However, despite these limitations, this approach was the most practical given the available resources.

7.2 Recommendations

- The findings of this analysis indicate that the regions of Friesland, Groningen, and Flevoland should be prioritised as key areas for AWE deployment due to their flat terrain, large-scale agricultural use, and low-density settlement patterns. These regions demonstrated the highest availability of suitable land and minimal topographical constraints. Promotion of co-use strategies in agricultural regions could help facilitate this development by integrating AWE deployment with existing farming operations, minimising disruption to landowners.
- Further, targeted ground truthing should validate the model's outcomes in these areas to confirm practical deployment feasibility. Ground surveys and aerial inspections in identified deployment areas could help to validate model predictions, particularly in zones with unclassified buildings, land use or misclassified features.
- The model results could be further improved with further investment/improvement of datasets for building classifications, particularly within OpenStreetMap and other sources, to reduce reliance on correction factors. This could be done in collaboration with local municipalities in priority areas or national geographic bodies to incorporate more detailed datasets on building types and land-use patterns.
- AWE developers should engage in operational radius optimisation to balance tether lengths with site availability. Sensitivity analyses highlighted that smaller operational radii (e.g., 300m) significantly increase potential deployment areas. Developers must also consider trade-offs involving airspace restrictions, wind resources, and ground station costs.

- It is recommended that this study is expanded to other countries with comparable geographic characteristics and lower population densities, such as Belgium, Denmark, and northern France. These regions may present greater deployment potential due to fewer land-use constraints and lower urban density.
- Future studies should adopt a more flexible approach that considers varying developer requirements. Each developer or organisation may have unique preferences, priorities, or constraints that influence site selection. Therefore, it is recommended to develop a framework that allows for customisation and adaptation to individual developer needs. Moreover, incorporating a comprehensive wind profile analysis is crucial to improve the accuracy and applicability of the results. By considering detailed wind profiles, including factors such as wind direction, speed, and turbulence, the analysis can provide more precise estimations of energy generation potential. This information is vital for optimising the layout and positioning of the technology, leading to more effective and efficient deployments.