ISSN 1831-9424

European Commission

# The Onshore Wind Potential of the EU and Neighbouring Countries

*ENSPRESO 2 - Update of the ENergy Systems Potential Renewable Energy SOurces data set*

Elsner, P., Collaer, J., Uihlein, A.

2025

Joint Research Centre

EUR 40184

**Contact information**
Name: Paul Elsner
Address: European Commission, Joint Research Centre (JRC), P.O. Box 2, NL-1755 ZG Petten, The Netherlands
Email: paul.elsner@ec.europa.eu
Tel.: +31 (224) 56-5290

**EU Science Hub**
https://joint-research-centre.ec.europa.eu

JRC139999

EUR 40184

| | | | | |
|---|---|---|---|---|
| Print | ISBN 978-92-68-23669-7 | ISSN 1018-5593 | doi:10.2760/1638274 | KJ-01-25-004-EN-C |
| PDF | ISBN 978-92-68-23668-0 | ISSN 1831-9424 | doi:10.2760/0396389 | KJ-01-25-004-EN-N |

Luxembourg: Publications Office of the European Union, 2025



How to cite this report: European Commission: Joint Research Centre, Elsner, P., Collaer, J. and Uihlein, A., *The Onshore Wind Potential of the EU and Neighbouring Countries,* Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/0396389, JRC139999.

## Contents

## Abstract

This report presents Europe's economically viable onshore wind energy potential at high geographical resolution (the JRC ENSPRESO 2 data set). It finds that in some scenarios, installable capacity and annual electricity generation are approximately double those previously estimated, indicating that onshore wind can play a much bigger role in the decarbonisation of Europe's energy system than previously assessed. It also finds that policy decisions on setback distances have a significant impact on the available potential. ENSPRESO 2 builds on the original ENSPRESO project (ENergy Systems Potential Renewable Energy SOurces) which concluded in 2018. The updated version operates at an unprecedented resolution of 1 $km^2$, incorporating newly available wind energy data sets and reflecting recent technological advances in wind energy technology, research and practices. ENSPRESO 2 therefore enables policymakers and energy planners to make fully up-to-date, spatially informed decisions about onshore wind energy deployment.

## Acknowledgements

We are grateful for expert advice on data and wind energy technology from our colleagues Evdokia Tapoglou and Lucy Mc Govern. We are also happy to acknowledge the support from a range of colleagues of JRC unit C.7 that helped us to collate and update the data set on setback distance regulations across Europe, including Drazen Tumara, Erhan Ozdemir, Ignacio Hidalgo Gonzales, Teodor Kuzov, and Anca Itul.

We also would like to thank Jake Badger (DTU) on his advice on wind resource data.

We acknowledge the comments and suggestions of the JERB reviewers Nigel Taylor, Sandor Szabo, and Georgia Kakoulaki which substantially improved the final document.



***Authors***

Paul Elsner

Julien Collaer

Andreas Uihlein

# 1 Introduction

The deployment of renewable energy is a key enabler to reach the European Union's climate goals: reducing greenhouse gas emissions by at least 55% by 2030 and becoming climate-neutral by 2050[1]. The REPowerEU plan, in particular, introduced a number of measures to reduce dependence on Russian fossil fuels and to increase the share of renewables. The revised Renewable Energy Directive establishes an EU wide target of at least 42.5% of renewable energy sources for 2030 (compared to an initial target of 32% target) and aims to reach 45% (*Directive (EU) 2023/2413*, 2023) which means almost a doubling of the existing share of renewable energy in the EU.

In order to accelerate the deployment of renewables, the new Renewable Energy Directive also includes provisions to simplify permitting processes for renewable energy projects. The Commission Recommendation on speeding up permit-granting procedures for renewable energy projects and facilitating Power Purchase Agreements asks Member States to identify so called "renewables acceleration areas". These are locations that are particularly suitable for the installation of plants for the production of energy from renewable sources; and where no significant environmental impacts are expected (*C(2022) 3219 final*, 2022). The Commission's Energy and Industry Geography Lab, managed by the JRC, is supporting Member States in identifying such "renewables acceleration areas". [2] A key element and the starting point for an optimal siting of renewables is a updated high resolution dataset on the potential for renewable energy.

In the past, the JRC developed an EU wide, transparent and coherent database of wind, solar and biomass energy potentials, the ENergy Systems Potential Renewable Energy SOurces, technical potentials (ENSPRESO) data.[3] As highlighted by Ruiz et al. (2019), its main objective was to provide input data for the energy system model JRC-EU-TIMES. The focus was on wind, solar, and biomass. Its spatial resolution was guided by the nomenclature of territorial units for statistics (NUTS) and data was aggregated to NUTS 2 level, as this was the spatial granularity required by the energy system model.

In the meantime, the need for an update (ENSPRESO 2) became clear in order to reflect recent technological advances in renewable energy generation and also to provide data on high spatial resolution (<1 km) to support the climate and energy transition of the EU.

The JRC has been working on ENSPRESO 2 with the aim to provide consistent data on the potential of renewable energy in Europe at high spatial resolution. ENSPRESO 2 goes beyond NUTS2 level and provides the technical RES potential. ENSPRESO 2 focuses on the EU27 but includes other European countries as well: UK, EFTA (Iceland, Liechtenstein, Norway, Switzerland), the Western Balkans (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, Serbia), and Türkiye.

This report presents the results of the work for ENSPRESO 2 related to onshore wind. The results for offshore wind will be published in a separate technical report shortly after the publication of this report, followed by a report on ENSPRESO 2 solar photovoltaics in 2025.

[1] https://eur-lex.europa.eu/eli/reg/2021/1119/oj

[2] https://joint-research-centre.ec.europa.eu/scientific-tools-databases/energy-and-industry-geography-lab_en

[3] https://data.jrc.ec.europa.eu/collection/id-00138

The ENSPRESO 2 datasets will be integrated into the Energy and Industry Geography Lab (EIGL) data portfolio and will also be available at the JRC data catalogue.[4]

[4] https://data.jrc.ec.europa.eu/collection/id-00138

# 2 Scope and methodology

This study introduces the results of our modelling activities for ENSPRESO 2 that estimate the potential for onshore wind. Substantial technological developments have taken place since the publication of the initial ENSPRESO 1 data set (Dalla Longa et al., 2018) and a subsequent continuous increase of capacity factors of wind turbines has been observed globally. The ten countries with the highest installed capacity all reported rising capacity factor values between 2010 and 2020 and beyond. This trend has been attributed to improvements in turbine technology and also increasing hub heights (Jung and Schindler, 2023). This means that better wind resources can be accessed more efficiently which overall leads to higher capacity factors and electricity generation.

The ENSPRESO 2 project aims to reflect these developments in the wind sector which leads to an improved energy generation of modern large-scale multi-MW wind turbines. Small wind turbines (250 kW) that were still part of the ENSPRESO 1 data are not considered. The potential for airborne wind energy (AWE) is also not analysed in the current update. Both technologies are either largely obsolete or have not reached technological readiness levels sufficient to support large-scale deployment.

The general ENSPRESO approach is to model several scenarios so that uncertainties in the input parameters, technological set-ups and the choice of policy options can be explored. In the case of onshore wind, the scenarios were based on different sets of setback distances from human settlements such as towns, villages, hamlets and individual houses.

The outputs of this study provide results both for the potential installable capacity of onshore wind turbines and also the potential electricity that could be generated annually. All data can be visualised and downloaded on the EIGL at 1 x 1 km resolution using a base raster provided by Eurostat GISCO[5]. Such 1 km resolution provide a detailed information about the spatial distribution of the RES potential. It also matches the resolution of the EU energy atlas that provides high-resolution maps of energy balances and scenarios from 2019 to 2050[6].

We aggregated the ENSPRESO 2 results to NUTS0, NUTS1, NUTS2, and NUTS3 levels and these layers are also available on the EIGL platform[7].

## 2.1 Onshore wind

### 2.1.1 Wind resource data

Reliable and accurate wind speed data is of central importance for wind potential assessment because the relationship between wind speed and wind power is non-linear. This means that

[5] https://ec.europa.eu/eurostat/fr/web/gisco/overview

[6] https://data.jrc.ec.europa.eu/dataset/76a6b550-253c-44a4-9a4c-d22079e7bf62

[7] https://energy-industry-geolab.jrc.ec.europa.eu/

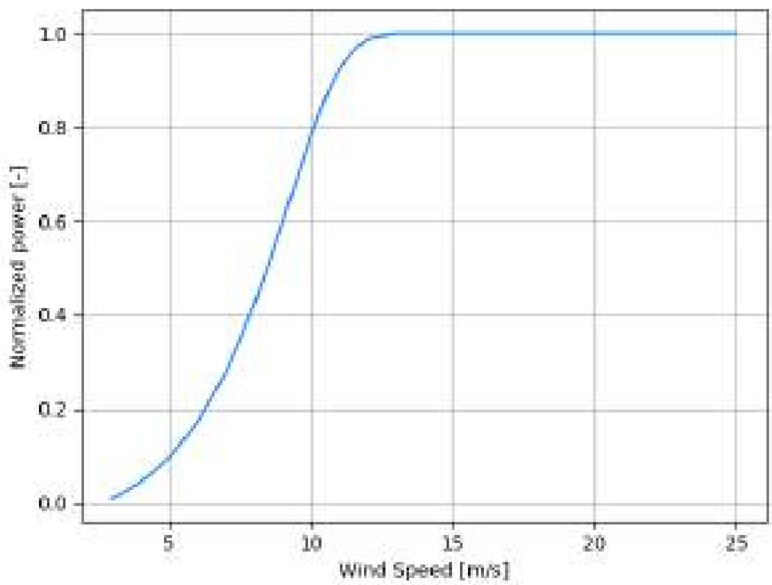
relatively small changes in wind speed will result in significant changes in wind power output of a wind turbine. This is because wind power is proportional to the cube of the wind speed ($v^3$).

$$Power = \frac{1}{2} C\rho A V^3$$

where
$\rho = Air\ density$
$C = Coefficient\ of\ performance\ of\ wind\ turbine$
$A = Swept\ area\ of\ the\ wind\ turbine\ blade$
$V = Velocity\ of\ wind$

The relationship between wind speed at hub height and the electrical power output of a wind turbine is illustrated by the power curve of that turbine (Figure 1). The power curve typically has a cubic shape, with power output increasing rapidly at low to moderate wind speeds and levelling off at higher wind speeds. Below the cut-in speed, no power is generated. The rated power wind speed denotes the point where the turbine produces its maximum power output, typically around 10-15 m/s. The power output then levels off and becomes insensitive to wind speed increases. At the cut-out wind speed the turbine shuts down to prevent damage, usually around 22-25 m/s.

**Figure 1**: Normalized composite power curve of a typical IEC Class 1 wind turbine




*Source: NREL*[8]

[8] (https://nrel.github.io/turbine-models/IEC_Class1_Normalized_Industry_Composite.html#power-curve)

The cubed relationship between wind speed and wind power has direct implications for European energy policies because a number of low-wind regions potentially do not have sufficient wind resources to support economically viable wind energy deployments.

In the past years, substantial efforts were made to generate more accurate and reliable wind resource data. Two data sets in particular can be highlighted in the context of onshore wind: the Global Wind Atlas (GWA) and the Global Atlas of Siting Parameters (GASP). The ENSPRESO 2 project benefitted substantially from such data improvements and could leverage their outputs. In the following sections, both datasets will be described further.

#### *2.1.1.1 Global Wind Atlas*

The Global Wind Atlas (GWA)[9] provides access to high-resolution wind data globally and for the generation of ENSPRESO 2 we used the output that was generated by GWA 3.3 that was released in June 2023. For onshore wind the GWA provides near-global coverage.

The GWA is generated by a cascading downscaling process that starts with the ERA5 re-analysis data set from the European Centre for Medium-Range Weather Forecasts (ECMWF) which simulates the atmospheric conditions between 2008 and 2017. Potential climate change related changes of wind patterns in the future are not reflected. This ERA5 layer has a spatial resolution of approximately 31 km (0.28° × 0.28°) at the equator, which corresponds to about 9 km (0.08° × 0.08°) at mid-latitudes. The data is then used to force the Weather Research and Forecasting (WRF) model which is a state of the art mesoscale numerical weather prediction system. The model uses a grid spacing of 3 km and outputs a set of generalized wind climates.

In a second step, this mesoscale data is downscaled again to microscale level with the Wind Atlas Analysis and Application Program (WAsP) that was developed by the Danish Technical University (DTU). WAsP calculates local wind climates at five heights (10 m, 50 m, 100 m, 150 m and 200 m above ground level) at a spatial resolution of 250 m. Users of the GWA have the opportunity to download wind resource information in a range of formats and units. The latest version 3 of the GWA offers mean wind speed, mean wind density, and also CF for reference turbines of IEC classes I, II, and III.

#### *2.1.1.2 Global Atlas of Siting Parameters*

The Global Atlas of Siting Parameters (GASP) project has the objective to reduce the levelized costs of energy (LCOE) of wind project by providing highly resolved data sets that quantify extreme wind conditions. This information is of substantial benefit for wind energy planners as they can avoid to place turbines in dangerous wind environments that were not designed to withstand extreme conditions. Before the publication of GASP, the assessment of localised wind climates had to rely

[9] www.globalwindatlas.info

mainly on *in-situ* measurements. Such measurements, however, were often short-term and sensitive to potentially missing data of extreme wind events.

Extreme wind exceed normal operating conditions and can potentially cause damage to the structural integrity of a wind turbine. These conditions can vary depending on the location and turbine design. Siting information on extreme wind conditions helps to optimize the financial viability of wind projects because the correct choice of design turbine classes and improved maintenance plans. By this, unnecessary costs for over-designed turbines can be avoided. The selection of the appropriate turbine designs also leads to higher annual energy production. Studies have shown that a IEC-appropriate turbine generates up to 50% more power than over-designed turbines that often have smaller diameters because they were optimised for stronger wind climates (Fingersh et al., 2006).

The GASP project is leveraging GWA data sets but also uses additional reanalysis input in the form of the Climate Forecast System Reanalysis (CFSR) dataset (Larsén et al., 2021). CFSR data is used to estimate extreme wind conditions. This is then followed by downscaling the flow from a spatial resolution of 40 km to a local scale of 275 m using a range of models, including the microscale model LINCOM (Larsén et al., 2022).

GASP provides a suit of parameters that that describe extreme wind conditions, including flow inclination, shear exponent, air density for extreme winds, the 50-year wind at three heights (50, 100, and 150 m), and turbulence. This allows it to make wind turbine IEC class recommendations according to the IEC-61400 standard (International Electrotechnical Commission, 2005). This industrial standard aims to ensure that wind turbine designs and installations are appropriate for local wind climates and so that turbines can withstand expected extreme weather conditions that they are likely to encounter during their life span.

### 2.1.2 Modelling approach and model criteria

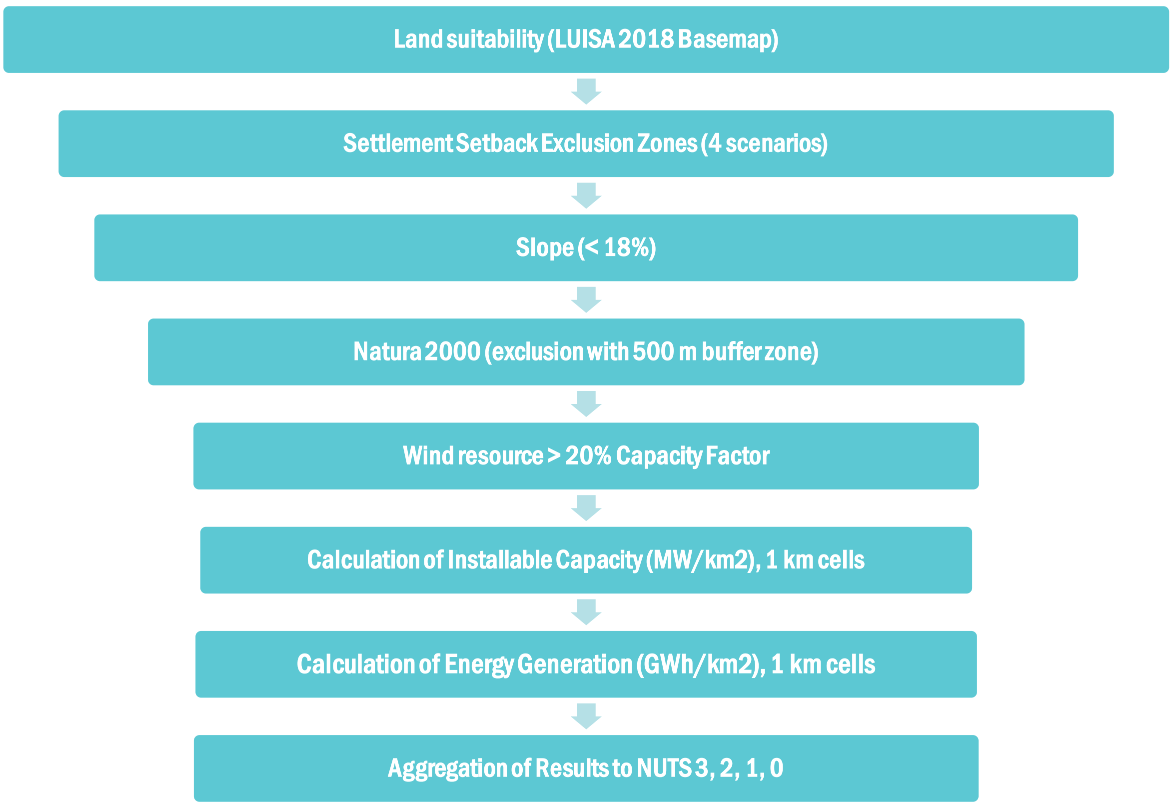
This section outlines our modelling approach for estimating Europe's onshore wind potential. When undertaking renewable energy potential analysis, it is common to distinguish between different types of "potential" (Brown et al., 2016; Hoogwijk et al., 2004). Briefly put, the *theoretical* potential denotes the total energy content of the wind; the *geographical* potential describes the energy that could be generated after a number of geographical constraints are taken into account; the *technical* potential is wind power generated at the geographical potential including energy losses due to the power density of the wind turbines; and the *economic* potential outlines the technical potential that could be economically implemented, i.e. can meet minimum profitability expectations of private developers. The *market* potential is describing that part of the economic potential that is viable after policy incentives and competition from other energy sources is taken into account. Each category narrows down the previous one as it applies additional limitations and constraints.

Recently, an additional potential type has emerged in the academic debate that overlaps potential types listed above. This is the *feasible* potential which delineates the achievable economic potential that accounts for market, organizational and social barriers (Jäger et al., 2016; McKenna et al., 2022). The feasible potential has some similarities with the *implementation* potential that was defined in the early 1990's but failed to become established in the wind research community back then. The implementation potential refers to the amount of economic potential that can be implemented within a certain timeframe, taking (institutional) constraints and incentives into account (van Wijk and Coelingh, 1993).

It should be noted that the above described potential categories are relatively loosely defined and regularly interpreted in different ways and overlap. In the context of ENSPRESO 2 we consider our output to describe the *economically viable* potential because we employ a minimum wind turbine capacity factor threshold from which we assume that wind farms would be able to operate in an economically feasible mode. At the same time, we also would like to emphasize that we did not undertake localised cost modelling that determines actual levelized costs of energy (LCOE) at specific locations. This was out of the scope of the project.

In general, we follow the general modelling approach that was used for ENSPRESO 1 (Dalla Longa et al., 2018; Ruiz et al., 2019) and other wind energy assessments that have been conducted (McKenna et al., 2022; Miyake et al., 2024). The process exhibits a series of cascading overlay operations for which we created a wide range of input spatial data sets (Figure 2). Each of these steps, its assumptions and associated data sources will be discussed in more detail in the following sections.

**Figure 2.** Conceptual framework of ENSPRESO 2 modelling to determine the online wind potential




*Source: JRC*

### 2.1.3 Land suitability

The availability of up-to-date and highly resolved land cover information is of central importance for modelling the wind potential. Land cover serves as a critical proxy for the suitability for onshore wind developments. It can also be used to identify the location of unsuitable areas and to delineate exclusion buffers around them if required.

A number of landcover data sets are publicly available and a comprehensive overview of landcover data in the global and European context is provided by García-Álvarez et al. (2022). The core land cover requirements for this project were high spatial granularity, a validated accuracy, and the implementation of a comprehensive landcover classification scheme that can be used to classify suitability/non-suitability for wind energy use.

The original ENSPRESO 1 project (Ruiz et al., 2019) employed the CORINE Land Cover (CLC) dataset as core landcover data source. CLC is an EUropean-wide land cover and land use database that provides a harmonized and consistent classification of land cover and land use across Europe[10]. It identifies 44 land cover classes which are hierarchically organised and can be grouped into the following categories: artificial surfaces (urban areas, infrastructure, etc.), agricultural areas (arable land, permanent crops, etc.), forests (broad-leaved, coniferous, mixed, etc.), wetlands (inland wetlands, coastal wetlands, etc.), and water bodies (rivers, lakes, etc.). The limitation of CLC, however, is its spatial resolution: The CLC data has a spatial resolution of 100 meters for linear objects but the overall minimum mapping unit (MMU) is 25 ha. This makes it problematic for the intended production of a high resolution 1 $km^2$ output for ENSPRESO 2.

We instead opted to use the LUISA Base Map 2018 of the JRC's Land-Use based Integrated Sustainability Assessment modelling platform[11]. This data was developed by integrating information from multiple datasets, including the CORINE Land Cover maps, Copernicus Earth Observation products, OpenStreetMap by using a structured geospatial data fusion approach (European Commission. Joint Research Centre., 2021). The pixel size of the raster cells is 100 m and the MMU is 1 ha for artificial surfaces and 5 ha for non-artificial surfaces.

Compared to the CORINE Land Cover, the LUISA Base Map has significantly higher spatial and thematic resolutions, allowing more detailed identification of land classes for wind energy developments. The respective classification is detailed in Table 1.

**Table 1.** Classification key for onshore wind suitability and settlement layer definition

| LUISA 2018 Code | Landcover Class | Wind Suitability | Settlement |
|---|---|---|---|
| 1111 | High density urban fabric | No | Yes |
| 1121 | Medium density urban fabric | No | Yes |
| 1122 | Low density urban fabric | No | Yes |
| 1123 | Isolated or very low density urban fabric | No | Yes |

[10] https://land.copernicus.eu/en/products/corine-land-cover

[11] Joint Research Centre Data Catalogue - LUISA Base Map 2018 - European Commission (europa.eu)

| LUISA 2018 Code | Landcover Class | Wind Suitability | Settlement |
|---|---|---|---|
| 1130 | Urban vegetation | No | Yes |
| 1210 | Industrial or commercial units | No | Yes |
| 1221 | Road and rail networks and associated land | No | No |
| 1222 | Major stations | No | Yes |
| 1230 | Port areas | No | Yes |
| 1241 | Airport areas | No | Yes |
| 1242 | Airport terminals | No | Yes |
| 1310 | Mineral extraction sites | No | No |
| 1320 | Dump sites | No | No |
| 1330 | Construction sites | No | Yes |
| 1410 | Green urban areas | No | No |
| 1421 | Sport and leisure green | Yes | No |
| 1422 | Sport and leisure built-up | Yes | Yes |
| 2110 | Non irrigated arable land | Yes | No |
| 2120 | Permanently irrigated land | Yes | No |
| 2130 | Rice fields | Yes | No |
| 2210 | Vineyards | Yes | No |
| 2220 | Fruit trees and berry plantations | Yes | No |
| 2230 | Olive groves | Yes | No |
| 2310 | Pastures | Yes | No |
| 2410 | Annual crops associated with permanent crops | Yes | No |
| 2420 | Complex cultivation patterns | Yes | No |
| 2430 | Land principally occupied by agriculture | Yes | No |
| 2440 | Agro-forestry areas | No | No |
| 3110 | Broad-leaved forest | No | No |
| 3120 | Coniferous forest | No | No |
| 3130 | Mixed forest | No | No |
| 3210 | Natural grassland | Yes | No |
| 3220 | Moors and heathland | No | No |
| 3230 | Sclerophyllous vegetation | Yes | No |
| 3240 | Transitional woodland shrub | Yes | No |
| 3310 | Beaches, dunes and sand plains | Yes | No |
| 3320 | Bare rock | Yes | No |
| 3330 | Sparsely vegetated areas | Yes | No |
| 3340 | Burnt areas | Yes | No |
| 3350 | Glaciers and perpetual snow | No | No |
| 4000 | Wetlands | No | No |
| 5110 | Water courses | No | No |
| 5120 | Water bodies | No | No |
| 5210 | Coastal lagoons | No | No |
| 5220 | Estuaries | No | No |

| LUISA 2018 Code | Landcover Class | Wind Suitability | Settlement |
|---|---|---|---|
| 5230 | Sea and ocean | No | No |

*Source: JRC*

### 2.1.4 Setback distances

Setback distances to settlements are highly relevant for wind energy planning and primarily related to concerns about health and safety aspects, environmental impacts, and aesthetics. A central concern is noise as wind turbines emit sound from the mechanical operation of the turbine and the aerodynamic noise of the blades moving through the air. Setback distances help to minimize the impact of noise on nearby residents and also to sensitive natural areas. Setback regulations are also important to protect against potential hazards such as ice throw, where ice accumulates on turbine blades and is subsequently thrown off. The unlikely event of a turbine or blade failure where debris could fall outside the turbine's footprint needs also to be considered. Shadow flicker is another concern as wind turbine blades can cast moving shadows on nearby buildings and residences.

Since ENSPRESO 1 (Dalla Longa et al., 2018), the setback distances regulations have often changed and needed to be updated. The legislation in many countries and regions is regularly extremely complex and delegated to various administrative levels and authorities. In general, there are three approaches to define setback distances: i) purely based on distance; ii) based on noise levels; and iii) based on wind turbine dimensions such as hub height and tip height. In the first case, the setback distance could be directly used while for the latter two cases, some assumptions had to be made regarding typical turbine type and height.

Furthermore, some countries use a detailed cadastral classification of settlements and buildings (e.g. residential areas, commercial areas, single buildings, buildings in rural environments) when determining set back distances. Examples are using different values depending on use categories such as residential areas with increased protection requirements (hospitals, schools), residential buildings in agricultural environments; or buildings located outside dedicated residential areas or the built environment. Setback distance regulations might also differ depending on capacity of the wind turbine itself.

The situation becomes even more complicated when considering that the legal definitions of "building", "residential area" or "settlements" can differ between countries. Also, often setback distances are set on a regional level; sometimes even at municipal level. Some countries do not have regulations in place but are handled within the individual permit application for each wind project. Finally, setback distances are sometimes different for repowering projects compared to new developments.

In the framework of Europe-wide ENSPRESO 2 project, we therefore needed to adopt a simplified approach and included only setback distances to buildings, regardless if they are formally part of a municipality or not. Other entities such as areas regulated by water protection, airports, radar and weather measurement installations, railway network, power transmission lines, motorways, and military installations were not buffered. The main reason for not including these were (a) the plethora of individual regulations across Europe and (b) the non-availability of coherent European data sets. This is particularly the case for military infrastructure data which is often classified.

Substantial effort was invested to collect up-to-date national and sub-national set back regulations. However, it needs to be noted that for some countries information on specific setback distances is potentially outdated or not fully accurate. For some regions generalized assumptions had to be made; e.g. using setback distances from neighbouring regions or countries (Table 2). For other countries, excellent overviews are available which explain all the details of the regulations.[12] Overall, we would like to emphasise that the regulatory environment for setback regulations is in constant flux and often subject to localised planning and zoning laws. We therefore caution that the listed general regulations in Table 2 might be incomplete or outdated despite all efforts to collect up-to date information from all countries.

**Table 2.** Overview of setback distances applied

| Country | Region | NUTS code | Setback distance (m) | Comment |
|---|---|---|---|---|
| Albania | | AL | 2 000 | |
| Austria | Lower Austria | AT12 | 1 000 | Distance differs between type of area, 1200 m for general residential areas assumed (1) |
| Austria | Upper Austria | AT31 | 1 000 | Distance for newly built turbines > 0.5 MW |
| Austria | Burgenland | AT11 | 1 200 | Distance to settlements |
| Austria | Styria | AT22 | 1 000 | No regulation in place (2) |
| Austria | Carinthia | AT21 | 1 500 | Distance to permanently inhabited buildings and dedicated building land |
| Austria | Vienna | AT13 | 1 000 | No regulation in place (2) |
| Austria | Salzburg | AT32 | 1 000 | No regulation in place (2) |
| Austria | Tyrol | AT33 | 1 000 | No regulation in place (2) |
| Austria | Vorarlberg | AT34 | 1 000 | No regulation in place (2) |
| Belgium | Flanders | BE2 | 600 | Based on noise regulation (3) |
| Belgium | Wallonia | BE3 | 700 | 4x tip height (4) |
| Belgium | Brussels | BE1 | 10 000 | Wind project prohibited |
| Bosnia and Herzegovina | | BA | 2 000 | |
| Bulgaria | | | 500 | |
| Croatia | | | 500 | Restrictions prescribed in spatial plans at local level. 500 m is commonly being used |
| Cyprus | | | 850 | Distance greater than 850 m from an already established limit; also noise limits apply |
| Czechia | | | 500 | Based on noise regulation (3). Not very clear |
| Denmark | | | 700 | 4x tip height (4). Also noise limits apply |
| Estonia | | | 600 | Based on noise regulation (3) |
| Finland | | | 550 | Based on noise regulation (3) |

[12] For example, the Fachagentur Windenergie provides an excellent – and regularly updated – overview of the regulations in all Federal States of Germany: https://www.fachagentur-windenergie.de/aktuelles/detail/abstandsempfehlungen-in-den-bundeslaendern/

| Country | Region | NUTS code | Setback distance (m) | Comment |
|---|---|---|---|---|
| France | | | 500 | |
| Germany | Baden-Württemberg | DE1 | 700 | Distance to purely residential areas, mixed areas and commercial areas |
| Germany | Bavaria | DE2 | 1 800 | 10x tip height (4) |
| Germany | Berlin | DE3 | 1 000 | No regulation in place (2) |
| Germany | Brandenburg | DE4 | 1 000 | |
| Germany | Bremen | DE5 | 620 | 620 m to residential areas and lower distance to other areas |
| Germany | Hamburg | DE6 | 500 | 500 m to residential areas and 400 m to individual buildings |
| Germany | Hesse | DE7 | 1 000 | |
| Germany | Mecklenburg-Vorpommern | DE8 | 1 000 | |
| Germany | Lower Saxony | DE9 | | 2x tip height (4) |
| Germany | North Rhine-Westfalia | DEA | 1 000 | |
| Germany | Rhineland-Palatinate | DEB | 900 | 900 m to residential areas and 500 m to individual buildings |
| Germany | Saarland | DEC | 1 000 | No regulation in place (2) |
| Germany | Saxony | DED | 1 000 | |
| Germany | Saxony-Anhalt | DEE | 1 000 | No regulation in place (2) |
| Germany | Schleswig-Holstein | DEF | 500 | 500 m to residential areas and lower distance to other areas |
| Germany | Thuringia | DEG | 1 000 | 1000 m to residential areas and 600 m to individual buildings |
| Greece | | | 1 000 | |
| Hungary | | | 700 | |
| Ireland | | | 500 | Also, noise limits apply |
| Italy | | | 1 000 | National regulation foresee 200 m distance or 6x tip height; applied for all regions where no specific regulations apply or where regional regulations apply same limits |
| Italy | Sardegna | ITG2 | 700 | 700 m from nuclei and houses scattered in the countryside, intended for residential use |
| Kosovo | | XK | 2 000 | |
| Latvia | | | 800 | |
| Lithuania | | | 700 | |
| Luxembourg | | | 500 | 900 m distance to buildings; also noise limit applies |
| Malta | | | 1 000 | No regulation in place (2) |
| Netherlands | | | 600 | Based on noise regulation (3) |
| Poland | | | 700 | |
| Portugal | | | 500 | 500 m to rural settlements and urban land |
| Romania | | | 500 | Various technical norms and guidelines available. Most wind farm planning documents mention 500 m (or 3x hub height) |
| Slovakia | | | 550 | Based on noise regulation (3) |
| Slovenia | | | 1 000 | No regulation in place (2) |

| Country | Region | NUTS code | Setback distance (m) | Comment |
|---|---|---|---|---|
| Spain | | | 1 000 | National regulation applied for all regions where no specific regulations apply |
| Spain | Baleares | ES53 | 1 000 | 1000 m around settlements and urban centres |
| Spain | Castilla y Leon | ES41 | 500 | No regulation in place (2) |
| Spain | Canary islands | ES70 | 400 | |
| Spain | Canary islands | ES70 | 400 | 400 m distance to inhabited areas for turbines > 900 kW |
| Spain | Pais Vasco | ES21 | 400 | Noise from wind turbines should not be heard from a distance of 400 m |
| Spain | Asturias y Cantabria | ES12 & ES13 | 500 | 500 m distance to rural nuclei and scattered buildings; larger distance to other areas |
| Spain | Galicia | ES11 | 500 | 500 m distance from rural centers, sectorised urban or developable land |
| Spain | Navarra | ES22 | 1 000 | Distance to urban centres |
| Spain | Valencia | ES52 | 1 000 | Distance to urban centres |
| Spain | Castilla-La Mancha | ES42 | 500 | No regulation in place (2) |
| Sweden | | | 600 | Based on noise regulation (3) |
| Turkiye | | TK | 1 000 | No regulation in place (2) |
| United Kingdom | England | UK | 800 | Adopted from ENSPRESO 1 |
| United Kingdom | Wales | UKL | 500 | Adopted from ENSPRESO 1 |
| United Kingdom | Northern Ireland | UKN | 500 | Adopted from ENSPRESO 1 |
| United Kingdom | Scotland | UKM | 2 000 | Adopted from ENSPRESO 1 |

1 According to IG Windkraft, distances differ between 750 and 2 000 m depending on type of residential area. 1 200 m is the distance to "dedicated residential building land and special building land area with increased protection requirements, e.g. hospital, school, retirement home".

2 Setback distance assumed based on other regions

3 Distances were assumed as follows: 500 m for 50 dB (night), 550 m for 45 dB (night), 600 m for 37-45 dB (night)

4 Assuming 180 m tip height

*Source: JRC*

To model the impact of varying setback distance regulations it is important to employ robust and consistent data on the location of settlements and individual dwellings from which buffer zones can be drawn to estimate the significance of set-back regulations.

Several data sets were considered. This included using settlement information provided by the Openstreetmap project. OpenStreetMap (OSM) is a global collaborative project to create a free editable map of the world (Minghini and Frassinelli, 2019). The geographic database OSM allows users to contribute and edit map data and can be used free of charge. OSM data includes detailed spatial information about buildings and settlements which makes it a candidate for being the base layer for our setback distance analysis. However, the fact that OSM largely relies of volunteered geographic information (VGI) also means that it is edited by a wide range of volunteers with varying levels of mapping skills. The completeness and quality of its annotations are heterogeneous across different geographical locations (Vargas-Munoz et al., 2021). An example is the Lombardy region in Italy where more than 50% of the buildings that are registered in official cadastral data were not represented in OSM data (Brovelli and Zamboni, 2018). Such spatial inconsistencies are problematic for the ENSPRESO 2 study as we required data that provides coherent Europe-wide reliable data.

Another candidate data set for modelling setback distances was the World Settlement Footprint (WSF) which is a global data set produced by the German Space Agency (DLR). It consists of a binary layer that outlines settlements in 10 m resolution[13]. The WSF is based on earth observation data collected by the Sentinel 1 and Sentinel 2 satellite missions of the European Copernicus programme and aims to outline human settlements on a global scale.

Its model architecture is based on the hypothesis that settlements are stable features and can therefore be identified by time series data. The modelling approach consisted of using temporal statistics in combination with a complex analysis chain using reference building outlines and binary Random Forest classification. This was concluded by a post-processing step that employed ancillary datasets to further reduce omission and commission errors (Marconcini et al., 2020).

For ENSPRESO 2 we tested the suitability of WSF data for setback distance modelling in two regions. The first one was a coastal area in Schleswig-Holstein in Germany. Close visual inspection and comparison with aerial photography data showed that WSF outlined buildings/settlements well. However, it also outlined a number of artificial structures such as grid masts and wind turbines.

This apparent property of WSF data to include some non-settlement structures was also observed in a second test case in Austria where we utilised the Green Transition Information Factory (GTIF) of the European Space Agency (ESA)[14]. The tool allows it to model set-back distances using either WSF data or official Austrian cadastral data. A comparison of both options showed that setback distances based on WSF data were substantially larger than when using official cadastral data. Based on the results of these tests it was concluded that the WSF data is not suitable for the determination of exclusion zones based on set-back distances for ENSPRESO 2.

We therefore decided to create a settlement data layer using the LUISA 2018 landcover data set (see classification scheme **Table 1**). This provided a binary layer with a spatial resolution of 100 m from which setback distance exclusion zones were generated. It should be noted, however, that some countries and regional administrations have separate setback distance regulations for municipalities and individual dwellings. Often, the distance requirements for individual dwellings are lower than for municipalities. As we did not have sufficient cadastral data available to further define our settlement layer into municipalities and individual dwellings, only buffer regulations for municipalities were used. This means that our approach is conservative as we potentially defined larger exclusion areas as was actual required in some places.

In order to cover the complexity of setback distances, we have decided to assess the influence of setback regulations by four different scenarios:

(a) The *high scenario* uses a setback distance of 500 m which is the considered to be the approximate limit in terms of noise exposure for the population in the vicinity of wind farms (Merino-Martínez et al., 2021).

[13] https://download.geoservice.dlr.de/WSF2019/

[14] https://gtif.esa.int/

(b) The *mid scenario* uses a setback distance of 1000 m which is the modal value listed in Table 2 and therefore can be used as an established distance that is already used by many European administrations.

(c) The *low scenario* uses a setback distance in of 2000 m and is the largest setback distance actually implemented, according to Table 2. This scenario is therefore the most restrictive setting.

(d) The *reference scenario* uses the current regulations listed in Table 2 that are implemented at the beginning of the year 2024.

### 2.1.5 Slope

Areas with steep slopes are problematic for the construction of wind parks and the slope angle of a location is therefore an important factor to consider. A gentle slope of less than 5% is generally preferred for wind turbine placement (McKenna et al., 2022). Slope can affect the accessibility of the area for construction and maintenance, as steeper slopes make it more difficult to build roads and infrastructure which increases construction costs and logistical challenges (Wiser et al., 2019).

An additional factor is that the slope and azimuth of terrains influence flow patterns and cause localised turbulence pattern (Wu et al., 2019) that are not always reflected in generic wind resource data sets. A gentle slope creates a more consistent wind flow while steeper slopes can lead to turbulence effects and reduced wind speeds. In areas with complex topography, wind shear can be more pronounced which affects turbine performance and energy production (Huang et al., 2022). Slope has therefore an impact in both capital expenditure (CAPEX) and operating expenditure (OPEX).

Terrain slope also has an impact on noise propagation from wind turbines. In areas with steeper slopes, noise can be directed towards nearby residential areas. Finally, in terms of the environmental impact of wind parks, steeper slopes may lead to increased erosion or habitat disruption, particularly in the construction phase (Sessarego and Shen, 2020).

In terms of specific slope ranges, terrain with flat to gentle slopes of up to 5% is considered to be ideal for wind turbine placement, as they offer easy access, a minimal environmental impact, and a consistent wind flow. Moderate slopes between 10 – 20% can still be suitable for wind farms but require more careful planning microscale wind flow modelling. Steeper slopes of 20 – 30% or more are commonly challenging for wind turbine installation and require bespoke design modifications. Overall, the specific slope requirements for a wind energy project depend on various factors such as local regulations, environmental conditions, and project-specific constraints.

A wide range of slope thresholds have been employed in wind resource assessments. One example is the very restrictive threshold of 3% that was selected for the first ENSPRESO 1 study (Dalla Longa et al., 2018), 9% for an assessment of the United Kingdom (Price et al., 2018), 20% for a global analysis (Bosch et al., 2017), 30% for Germany (Blankenhorn and Resch, 2014; Luetkehus et al., 2013) and Europe (Ryberg et al., 2020), and 36% on China (Zhou et al., 2012). For the context of our ENSPRESO 2 project it was decided to adopt the conservative threshold of 18% to ensure that the potential estimation of ENSPRESO 2 would not be skewed by an overoptimistic slope parameter setting. For the calculation of slope data we used the 90 m Copernicus GLO-90 digital Surface Model (DSM)[15]. This DSM is derived from a revised version of the WorldDEM that included internal data correction such as the consistent flow of rivers, edited shore- and coastlines, and the removal of implausible terrain structures. The WorldDEM product is based on the radar satellite data acquired by the TanDEM-X Mission of German Aerospace Centre (DLR) and Airbus Defence and Space (Riegler et al., 2015).

### 2.1.6 Conservation Areas

It is general practice to exclude conservation areas from wind energy potential studies as to avoid disruption of sensitive ecosystems and to maintain the integrity of protected areas. Wind farms can harm species and habitats either directly (e.g., through bird collisions) or indirectly (e.g., through habitat disruption). Another factor is the maintenance of ecosystem services, as protected areas often provide essential services such as water filtration, soil formation, and climate regulation. Wind farms can disrupt these services and thereby compromise the benefits they provide to human societies.

For our analysis we used the areas designated as Natura 2000 sites as proxy for regions that should be excluded from wind developments. We also applied a generic 500 m distance buffer to all Natura 2000 areas. Natura 2000 is a network of protected areas in the European Union (EU) established under the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC). Natura 2000 sites are legally protected, and any development, including wind farms, must comply with the EU's environmental legislation.

Natura 2000 sites are designated to protect specific habitats and species. When assessing wind farm proposals near or in Natura 2000 sites, authorities must consider the cumulative impact of the development on the site's conservation objectives. This means evaluating the potential impacts of the wind farm in conjunction with other human activities in the area. In our analysis we have assumed Natura 2000 areas indicate the presence of protected species and habitats. The related data sets were as accessed via the depository of the European Environment Agency[16].

We also addressed the conservation and nature protection aspect by excluding land cover classes from the potential analysis that indicate sensitive environments, such as wetlands, moors & heathlands, and coastal lagoons (see Table 1). Due to the lack of consistent Europe-wide data, we did not include bird migration routes in the analysis.

### 2.1.7 Capacity Factors and reference turbines

The capacity factor (CF) of a wind farm can be defined as the percentage of a year that wind turbines operate with their full rated capacity. For example, a CF of 25% is equivalent to 2190 full load hours per year. The CF is a crucial parameter for the economic viability of a wind farm because it directly

---

[15] https://portal.opentopography.org/raster?opentopoID=OTSDEM.032021.4326.1

[16] https://www.eea.europa.eu/data-and-maps/data/natura-14/natura-2000-spatial-data

affects the project's revenue and profitability. As the CF determines how much energy can on average be generated over the course of a year, it influences economic indicators such as the return on investment (ROI) or levelized cost of electricity (LCOE) of a wind farm project. Lenders and investors therefore use the CF as key metric to assess the creditworthiness of a wind farm project. A higher capacity factor reduces the risk of the project, making it easier to secure financing and often also lowering associated interest rates. A high capacity factor can also improve the stability and reliability of the grid.

Capacity factors of modern wind turbines have risen continuously in the past decades. A recent study on the development of full load hours of German onshore turbines exemplifies this with a recorded CF of 14-20% in the year 2000, rising to 22–28% in 2020 and expected to reach up to 40% in 2030 (Borrmann et al., 2020). This trend has been observed globally as well, with the two main drivers being rising hub heights and improved turbine technology (Jung and Schindler, 2023).

To reflect such advances in the ENSPRESO 2 project we have adopted the capacity factor data information that is provided by the GWA because they are based on state-of-the art reference turbines for three IEC classes (see Table 3). However, the CF values of the GWA are essentially only based on the local wind conditions and the power curves of the respective reference turbines. This means that they represent more theoretical values without consideration of operational limitations that occur during the operation of wind farms.

To address this aspect, it is necessary to apply a loss factor which expresses the amount of energy that is lost due to issues such as equipment downtime, maintenance downtime, and environmental conditions. Loss factors can vary depending on the specific location and design of the wind farm. Examples of such operational issues are equipment failure, maintenance, wake effects and environmental conditions such as icing (Fields et al., 2021). An additional aspect is the decline of the wind farm performance over the period of its lifetime (Staffell and Green, 2014) which needs to be factored in as well when estimating the long-term average energy production over the life cycle of a wind park.

The loss factor is typically expressed as a percentage of the total potential energy production of the wind farm. A realistic estimation of such operational loss factors is a central consideration for estimating the actual energy output of a wind farm. A review of actual generation data of onshore wind turbines in Germany calculated an average loss factor of 17%. However, this value included an assumed 1.5% loss due to regulatory restrictions as well (Borrmann et al., 2020). The forward-looking NREL 2023 Electricity Annual Technology Baseline (ATB) data base[17] excluded regulatory issues and estimated for the year 2030 loss factors between 10.7% and 18%, depending on scenarios. These values reduced to 9.5% and 16% for the year 2050, as it is expected that the wind industry continues to benefit from advances in atmospheric sciences and forecasting so that dynamic wind plant control strategies can further limit wake effects.

For ENSPRESO 2 we decided to continue to apply a general loss factor of 15%, which was adopted in the original ENSPRESO 1 project as well (Dalla Longa et al., 2018) because this value is in agreement with range of loss factors discussed earlier.

[17] https://atb.nrel.gov/electricity/2023/land-based_wind

**Table 3.** Technical specifications of IEC reference turbines used in the Global Wind Atlas

| Turbine characteristics | Reference turbine IEC I | Reference turbine IEC II | Reference turbine IEC III |
|---|---|---|---|
| Rated power (MW) | 3.45 | 3.45 | 3.45 |
| Rotor diameter (m) | 112 | 126 | 136 |
| Hub height (m) | 100 | 100 | 100 |
| Design annual average wind speed (m/s) | 10 | 8.5 | 7.5 |
| Assumed wind density for power curve (kg/m³) | 1.225 | 1.225 | 1.225 |
| Cut-in wind speed | 3 | 3 | 3 |
| Full rated power at wind speed (m/s) | 12.5 | 11.5 | 11 |
| Cut-out wind speed 9(m/s) | 25 | 22.5 | 22.5 |

*Source: GWA*

In our final analysis of the onshore potential we also then applied a CF threshold of minimum 20% (after losses) to safeguard that the identified wind locations meet basic economic viability expectations. Areas that had a lower CF than 20% were therefore deemed unsuitable for onshore wind energy development and excluded.

For capacity calculations we continue to assume a power output of 3.45 MW for our reference turbine, similar to the original ENSPRESO 1 project (Dalla Longa et al., 2018). However, we raised the assumed hub height from 80 m to 100 m to reflect recent technological advances in the onshore wind industry's installation practices. A higher hub height makes it possible to access better and less disturbed wind flows. This in turn leads to better CF and associated electricity generation costs (Jung and Schindler, 2022; Satymov et al., 2022).

### 2.1.8 Capacity density

The capacity density can be defined as the ratio of the wind farm's rated capacity to its ground area, usually expressed in MW/km$^2$. Past assessment studies have used a range of capacity density assumptions and there is an ongoing debate about the appropriate capacity density for modern wind parks in both the onshore and the offshore domain (Enevoldsen and Jacobson, 2021; McKenna et al., 2022; Pryor et al., 2021; Pryor and Barthelmie, 2024). The original ENSPRESO 1 study adopted a unified value of 5 MW/km$^2$ for its onshore and offshore wind potential model. For ENSPRESO 2, we decided that it is more appropriate to employ different capacity densities for each domain.

A recent review (McKenna et al., 2022) reported that the power densities in academic studies on onshore potential ranged between 1.5 MW/km$^2$ (Bosch et al., 2017) and 18.6 MW/km$^2$ (McKenna et al., 2015). A more data oriented study investigated the power density of actual wind farms in Europe and this resulted in higher values. Densities ranged between 6.2 to 49 MW/km$^2$, with an average of 19.8 MW/km$^2$ (Enevoldsen and Jacobson, 2021). One of the reasons that is given for such discrepancy is that onshore wind farms have a relatively moderate size of 20 - 50 MW and are clustered in space. Because of the substantial distances between them, project developers do not have to consider wake optimisation across large areas.

For the onshore domain of ENSPRESO 2, we adopted an assumed maximum power density of 10 MW/km$^2$. This value has been employed by a number of other potential studies in the European context as well (Enevoldsen et al., 2019; McKenna et al., 2015; Ryberg et al., 2019).

### 2.1.9 Spatial aggregation of wind capacity and annual electricity generation

The analysis of the onshore wind potential was carried out on spatial resolution of the 100 m LUISA landcover data set. All other input data sets were resampled to that resolution and projected to the coordinate reference system (CRS) ETRS89-LAEA Europe. This CRS is also known by the EPSG Geodetic Parameter Dataset identifier EPSG:3035. It is a Lambert equal area projection and is recommended by the JRC for analytical work on continental Europe (Annoni et al., 2001).

The actual output resolution of ENSPRESO 2 onshore wind is 1 km$^2$. This means that the results of our availability analysis (carried out on 100 m level) needed to be aggregated to our reporting resolution of 1 km. Two output layers were created: First, the estimate of installable capacity in units of MW/km$^2$, and second the modelled annual electricity generation of GWh/km$^2$.

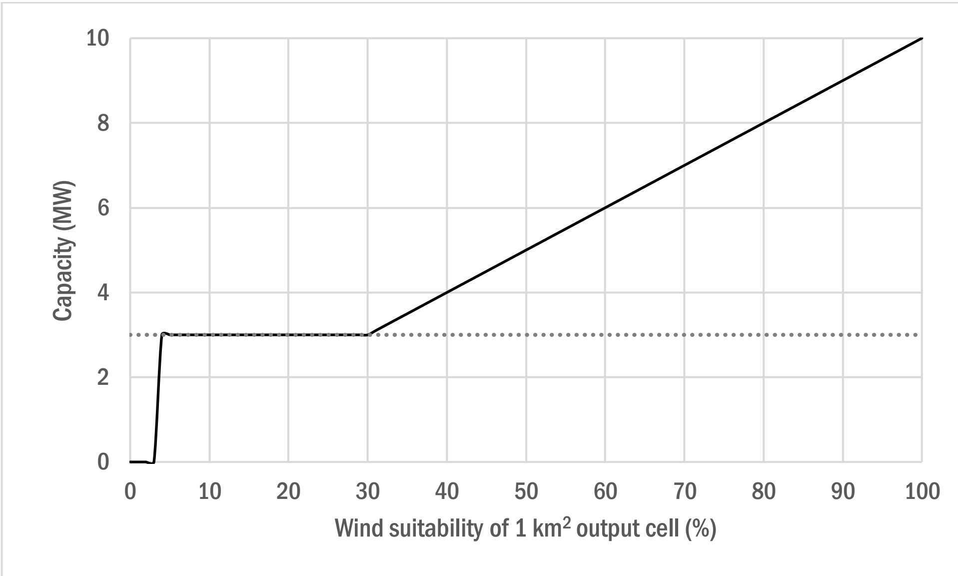
As outlined in the section on onshore power density, we assume a maximum capacity of 10 MW per 1 km$^2$ cell. This means that if the entire 1 km grid cell (equivalent to all 100 m cells from the land availability analysis) is deemed suitable for wind development, then the maximum capacity of 10 MW will be assigned to that 1 km$^2$ cell. Cells that have smaller suitable areas are respectively assigned smaller capacities, using a linear scaling process. This means that a 1 km$^2$ cell with 30% suitability will be assigned a capacity of 3 MW/km$^2$, which is equivalent to the capacity of one reference turbine.

However, fully applying this logic of linear scaling would mean that all 1 km$^2$ cells with less than 30% suitability would be assigned zero capacity. This would also mean that substantial wind potential could not be considered and therefore lead to an underestimation of wind potential. Such "small area problem" has been recognised by other authors (McKenna et al., 2022, 2014; Ryberg et al., 2020).

To avoid underestimation of capacity we used the approach to assign 3 MW also for those 1 km$^2$ cells that have suitable wind areas which are large enough to accommodate the physical footprint of a single turbine, i.e. its tower base and associated infrastructure. We assume that a minimum of 4 ha would be sufficient for this. This means that all 1 km$^2$ cells with at least 4% of wind suitability were assigned a single turbine capacity of 3 MW as well. Cells with less than 4% suitability were considered unsuitable for wind (see Figure 3).

The annual electricity generation was calculated using the respective capacity factor of all the suitable cells, using the respective CF of the reference turbine. This resulted in the second output layer that provide annual electricity generation on 1 km$^2$ level, expressed in units of GWh/km$^2$.

**Figure 3.** Assigning onshore wind capacity based on cell suitability.




*Source: JRC*

# 3 Results

This section introduces the key results of the ENSPRESO 2 study and will present the output with a series of example maps and figures.

## 3.1 Results for mid scenario (1000 m setback distance)

The core outputs of ENSPRESO 2 are:

(a) data on the installable capacity in terms of $MW/km^2$, and

(b) information about the annual electricity ($GWh/km^2$) that can be expected to be generated by the respective capacity, using localised turbine capacity factors.

Figures 4 and 5 show those outputs for the *mid-scenario* of 1000 m setback distance. It can be seen that most countries in central Europe have large regions with moderate installation capacities per 1 $km^2$ cells, meaning that wind parks could be developed there and contribute to the electricity supply. The highest installation capacities per 1 $km^2$ cell are limited to selected countries with low population densities, for example in eastern Europe (e.g. Hungary and Romania) and the Iberian peninsula.

Figures 6 and 7 show the national aggregates of both wind economically viable wind capacity and associated annual electricity generation. Spain is, by a substantial margin, the EU member state with the highest economically viable wind potential, followed by Romania and Sweden. The combination of Figures 6 and 7 also illustrates the importance of wind resource. For example, Italy has a higher onshore wind capacity than for Lithuania. Nevertheless, Lithuania records a higher electricity generation potential because of its better wind resource. A similar dynamic can be observed between Greece and Romania (higher installable capacity) and Estonia and Sweden (higher electricity generation), respectively.

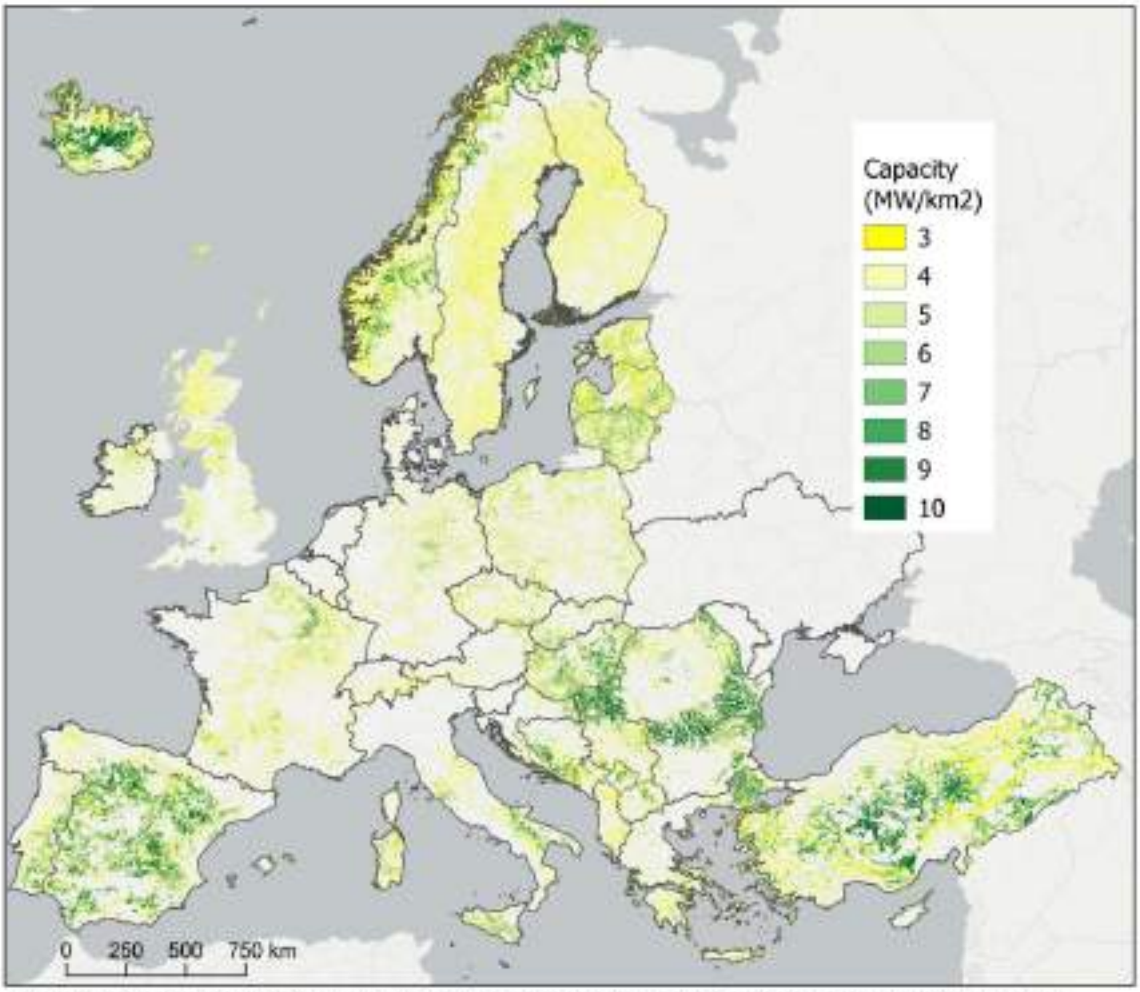
To illustrate the value of the spatial detail of ENSPRESO 2 we created two smaller scale maps that zoom into the annual electricity generation patterns of the Baltic region (Figure 8) and southern Italy, Albania, and mainland Greece (Figure 9). The Baltic region map clearly shows two distinct spatial patterns. For Germany, Denmark and Poland, the identified economically viable onshore wind potential consists of distinct clusters of hotspots of high generation. This means that wind energy planning will need to target such areas. For Sweden and Finland, on the other hand, the viable wind resource is more homogeneously distributed, with no clear high generation hotspots.

The Mediterranean example in Figure 9 also shows that economically viable wind resource in those countries is concentrated in smaller hotspots. In southern Italy, most of the significant clusters can be found in Apulia and Basilicata, with much less potential in neighbouring Calabria. For Greece, most resource clusters are concentrated in the Peloponnese Region and in Macedonia.

The full data set data is openly available and can be accessed via the EIGL data portal[18] of the JRC.

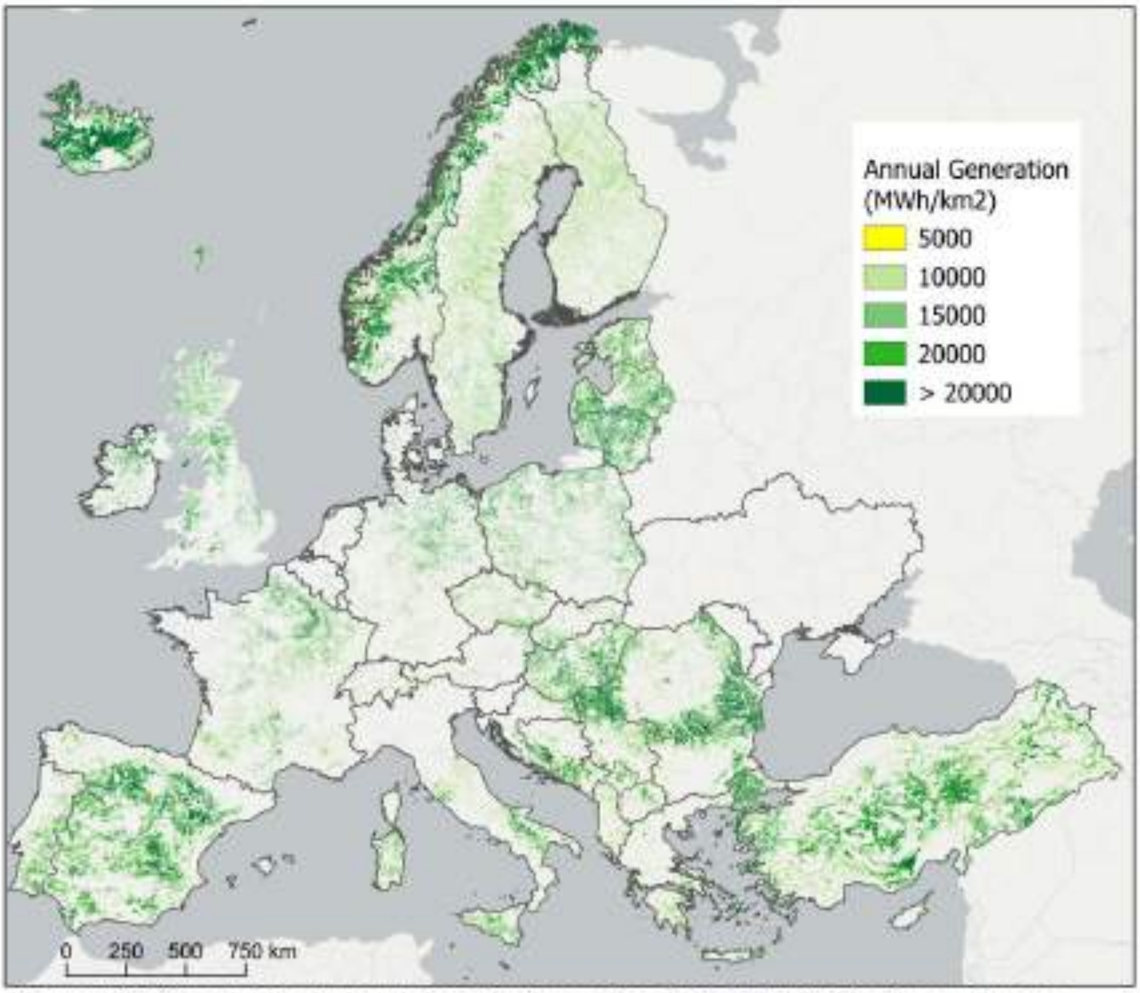
[18] https://energy-industry-geolab.jrc.ec.europa.eu/

**Figure 4.** Onshore wind capacity potential for 1000 m setback distance.



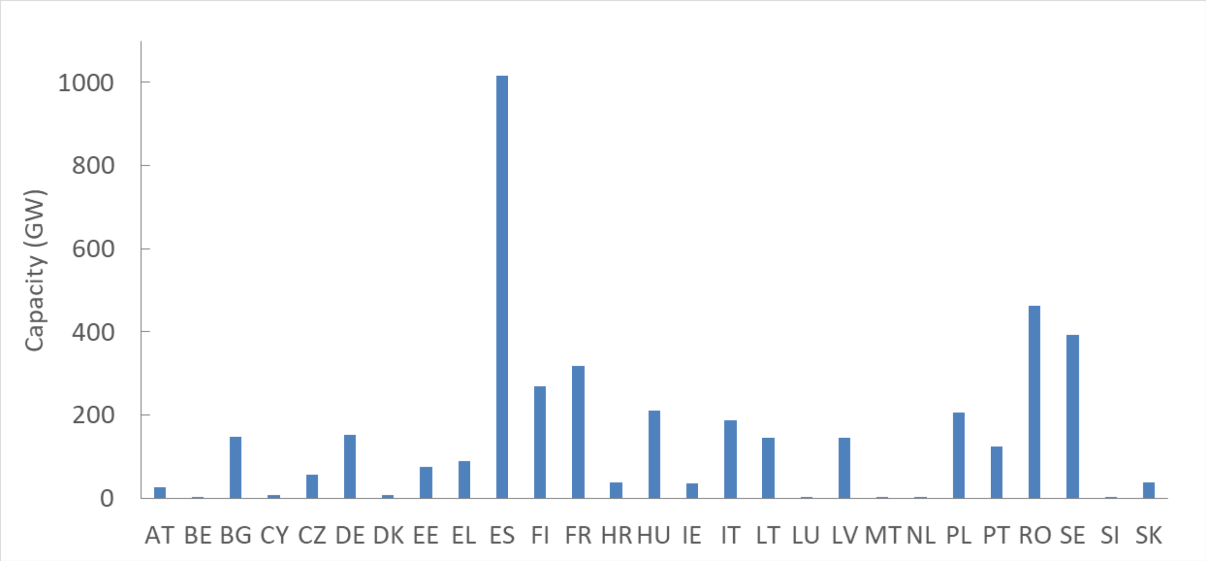

Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 5**. Onshore wind electricity generation potential for 1000 m setback distance



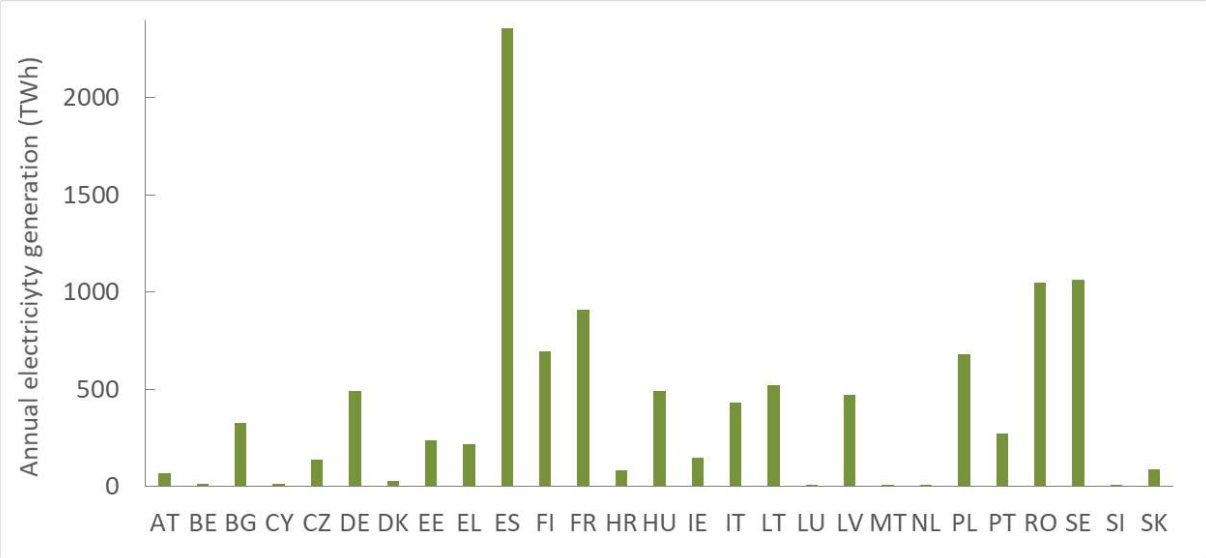

Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 6.** Economically viable onshore wind capacity for the 1000 m setback scenario, aggregated to national level




*Source: JRC*

**Figure 7.** Potential annual electricity generation for the 1000 m setback scenario, aggregated to national level




*Source: JRC*

**Figure 8.** Annual Generation, 1000 m setback distance, for Baltic Sea region.

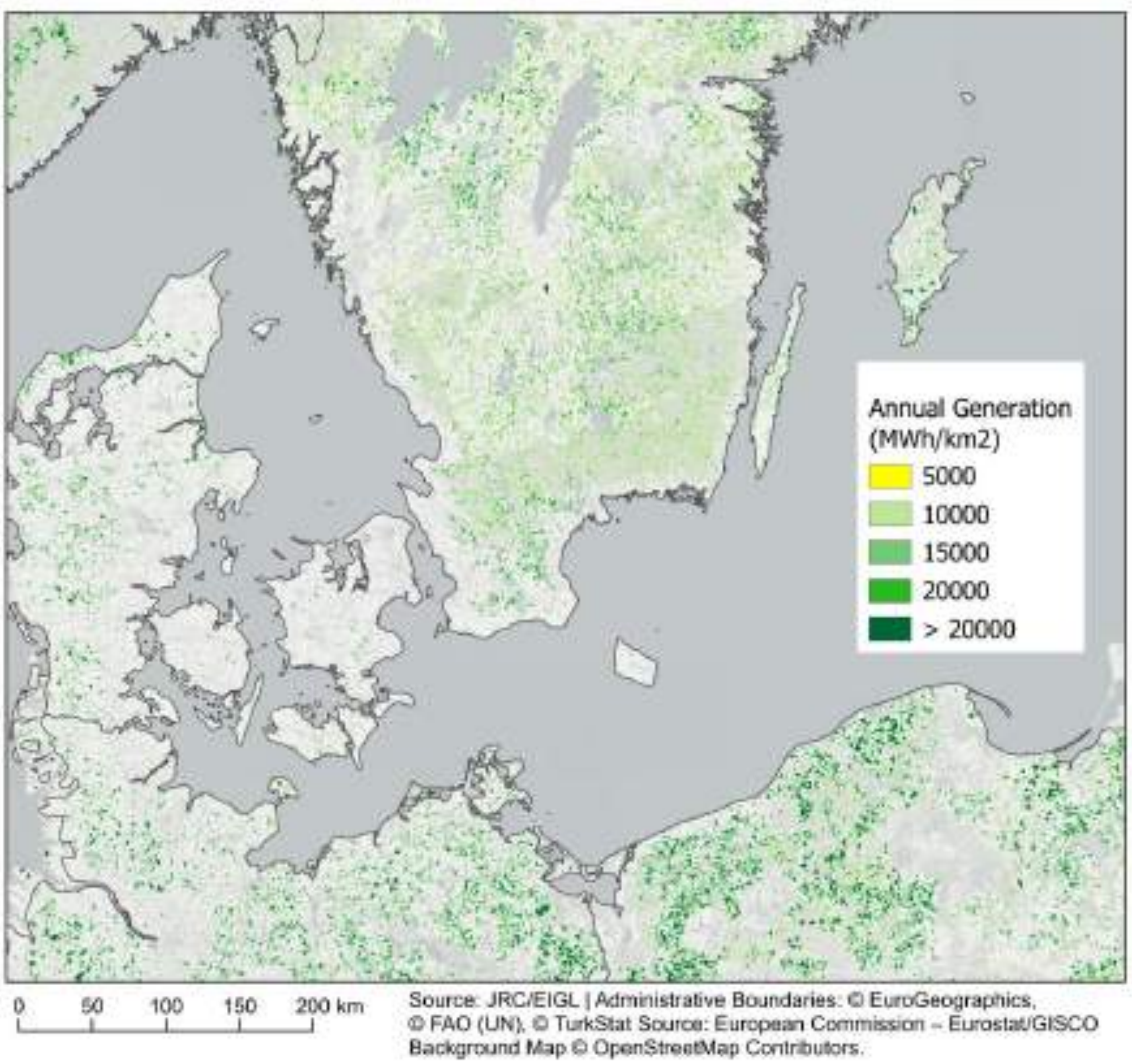
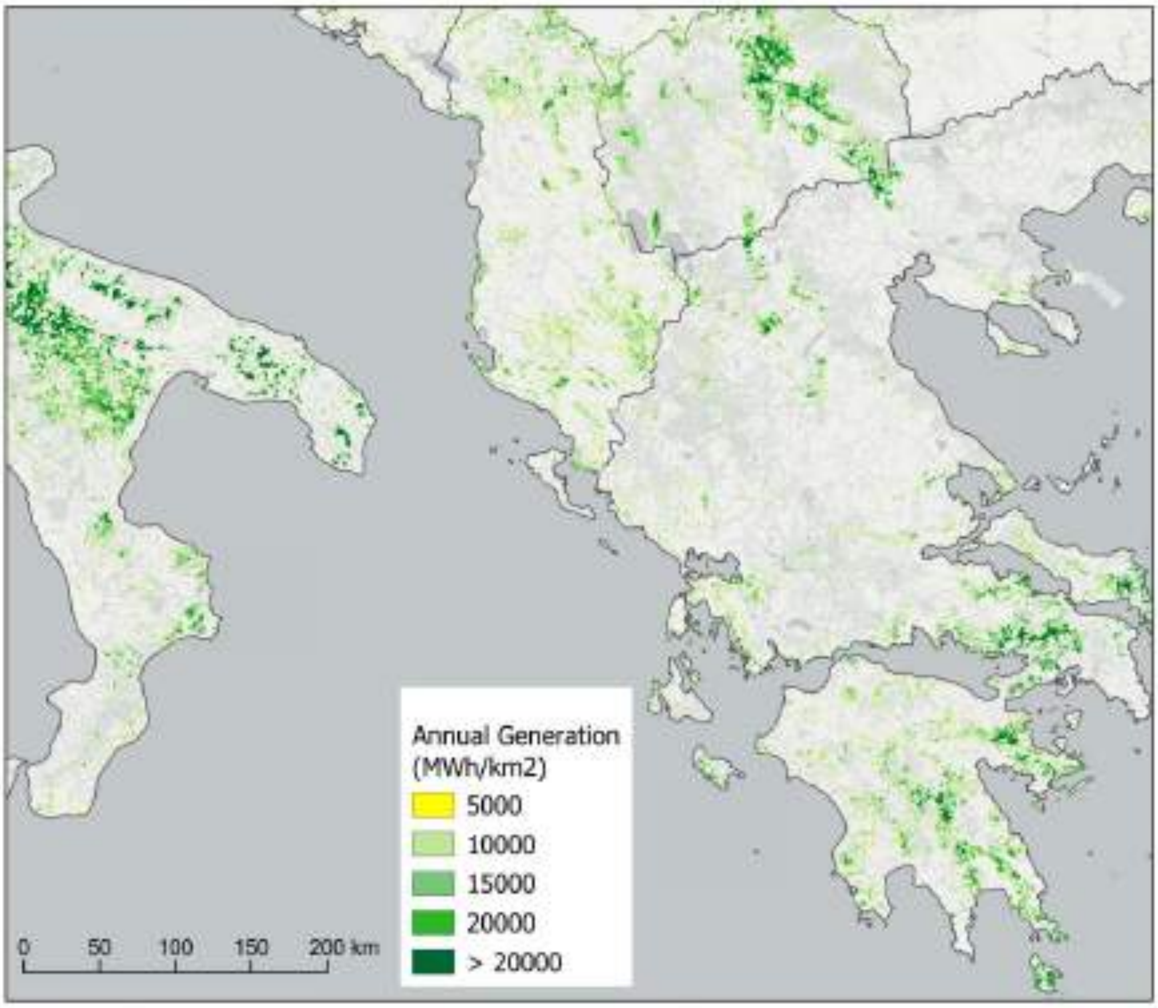


**Figure 9.** Annual Generation, 1000 m setback distance, for Southern Italy and mainland Greece.




Source: JRC/EIGL | Administrative Boundaries © EuroGeographics, © FAO (UN), © TurkStat
Source: European Commission – Eurostat/GISCO Background Map © OpenStreetMap Contributors.

## 3.2 Setback distance scenarios

The previous section focused in detail on the results of the *mid-scenario* with a 1000 m setback distance. As discussed in section 2.1.4, three additional scenarios were modelled for the ENSPRESO 2 project, using alternative setback distances of 500 m, 2000 m, and regulations that are in place in 2024.

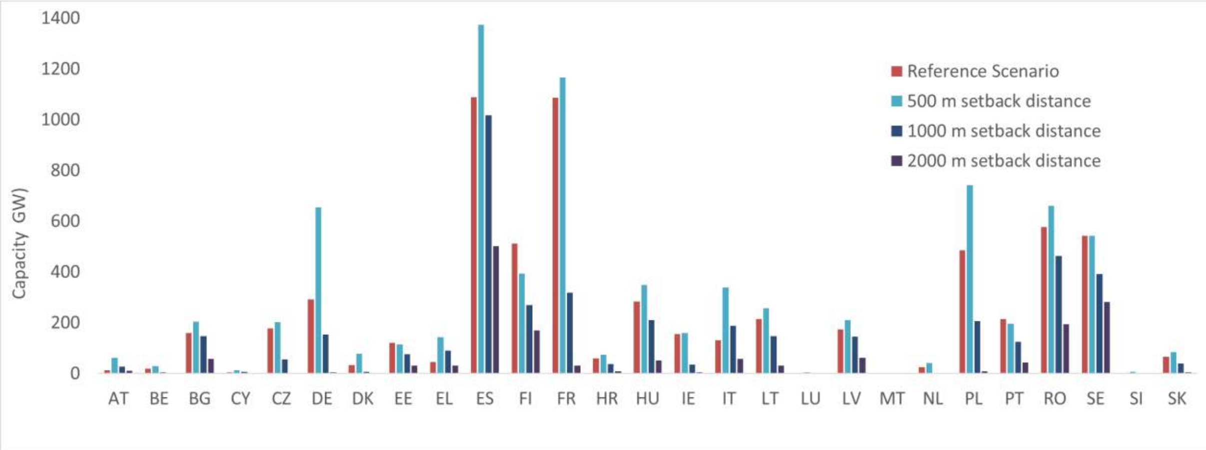
The impact of setback regulations on potential estimates is illustrated in Figures 10 and 11 which show the difference between the four setback distance scenarios. As can be expected, the 500 m setback assumption generates the highest potential and the 2000 m scenarios the lowest. However, the impact of setback changes varies significantly across EU member states and reflects the settlement structure, population distribution, and dominant landcover types. As an example, in countries such as Poland, Germany, Czechia, and Denmark the shift from 500 m to 1000 m reduces the potential by two-third. The even more restrictive setback distance of 2000 reduces the potential in those countries to near zero. Such impact is less dramatic in states with lower population densities, e.g. Finland, Sweden, Bulgaria, and Romania. Here, even a setback distance of 2000 m would result in sizable onshore wind potential.

The following series of maps illustrate this output and provides capacity and electricity generation maps for all four scenarios. Figures 12, 13 and 14 show the capacity potential and the spatial dynamics that are associated with different setback dynamics. For the 500 m setback scenario (Figure 12) a consistent capacity of 3-5 $MW/km^2$ can be found across Europe. Cells with very high capacity of up to 10 $MW/km^2$ are largely limited to lower populated regions such as south-east Europe and central Spain. These areas maintain most of their capacities in the 1000 m scenario (Figure 4). However, most of the densely populated regions in central Europe see their onshore wind capacities substantially reduced. This indicates that these areas are particularly sensitive to even relatively moderate changes to setback distance regulations.

The restrictive setback distances of 2000 m (Figure 13) would eradicate most of the economically viable wind potential in central Europe and also reduce substantial capacities to Spain and south-east Europe. Interestingly, most of Scandinavia is relatively insensitive to changes in setback distance assumptions and shows limited potential differences between scenarios.

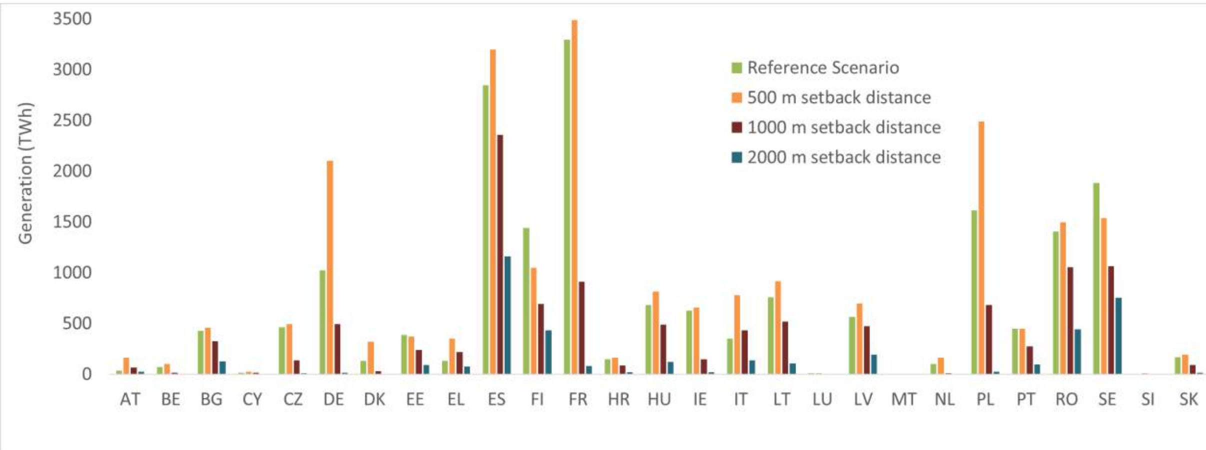
The same patterns can be seen in the maps that show the annual electricity generation per $km^2$ cell. However, the importance of wind resource is clearly evident. Whereas the 500 m capacity scenario displays quite uniform capacities across central Europe (Figure 12), the associated electricity generation map (Figure 15) shows much stronger patterns. Regions in northern Europe exhibit considerably higher production due to their better wind resources. Similar can be observed for Scandinavia where coastal areas along the North Sea are among the highest producing cells overall.

**Figure 10.** ENSPRESO 2 modelled installable onshore wind capacity for all four setback distance scenarios



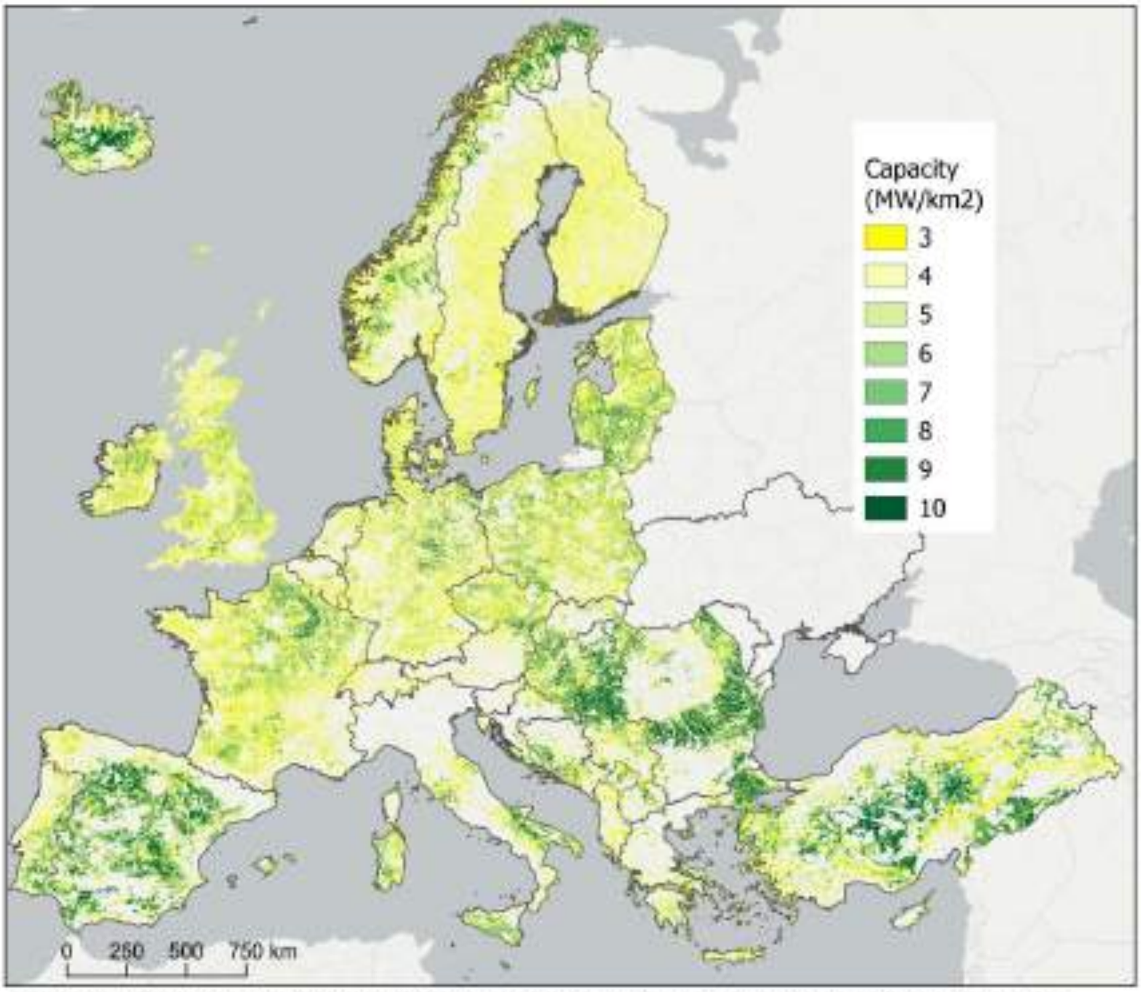

*Source: JRC*

**Figure 11.** ENSPRESO 2 modelled onshore wind annual electricity generation for all four setback distance scenarios



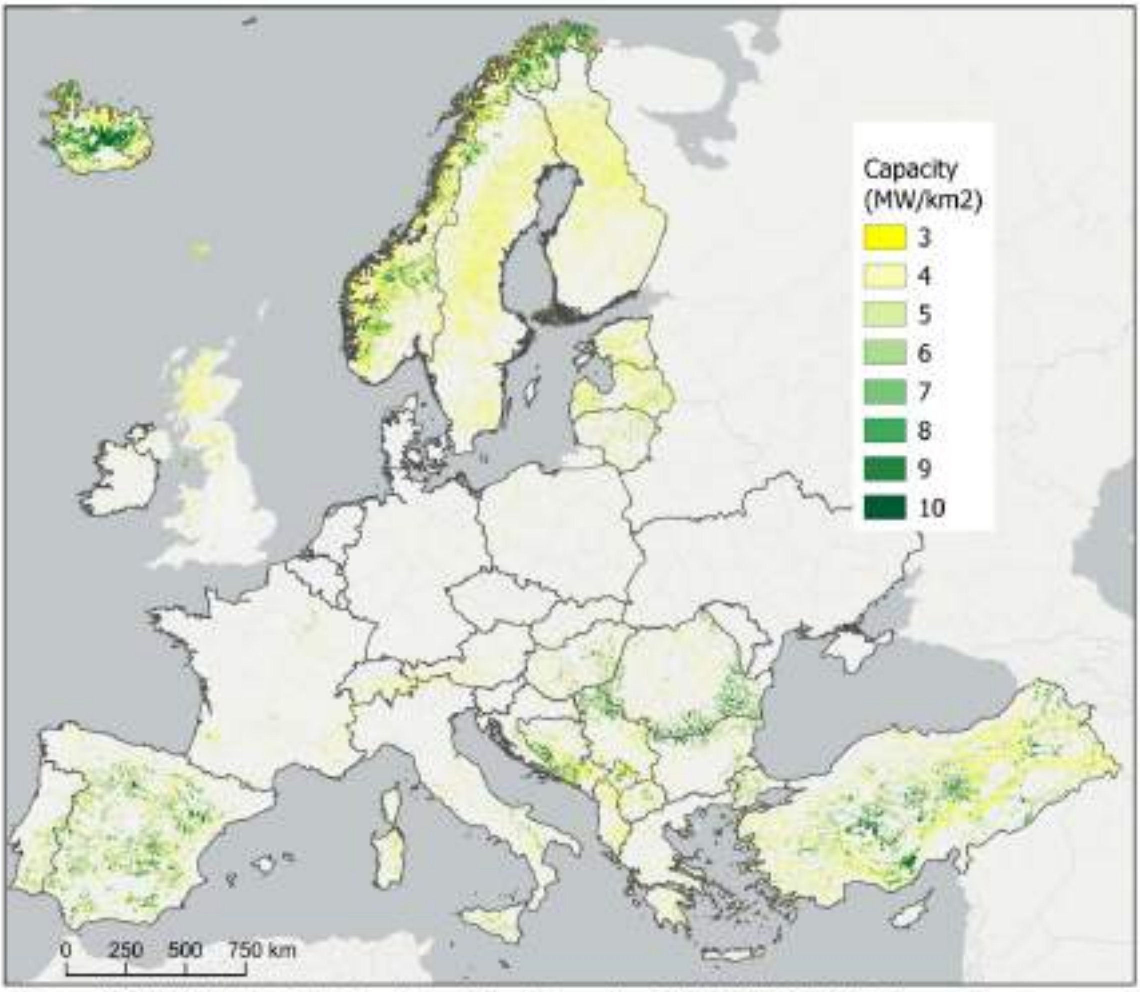

*Source: JRC*

**Figure 12**. Onshore wind capacity potential for 500 m setback distance



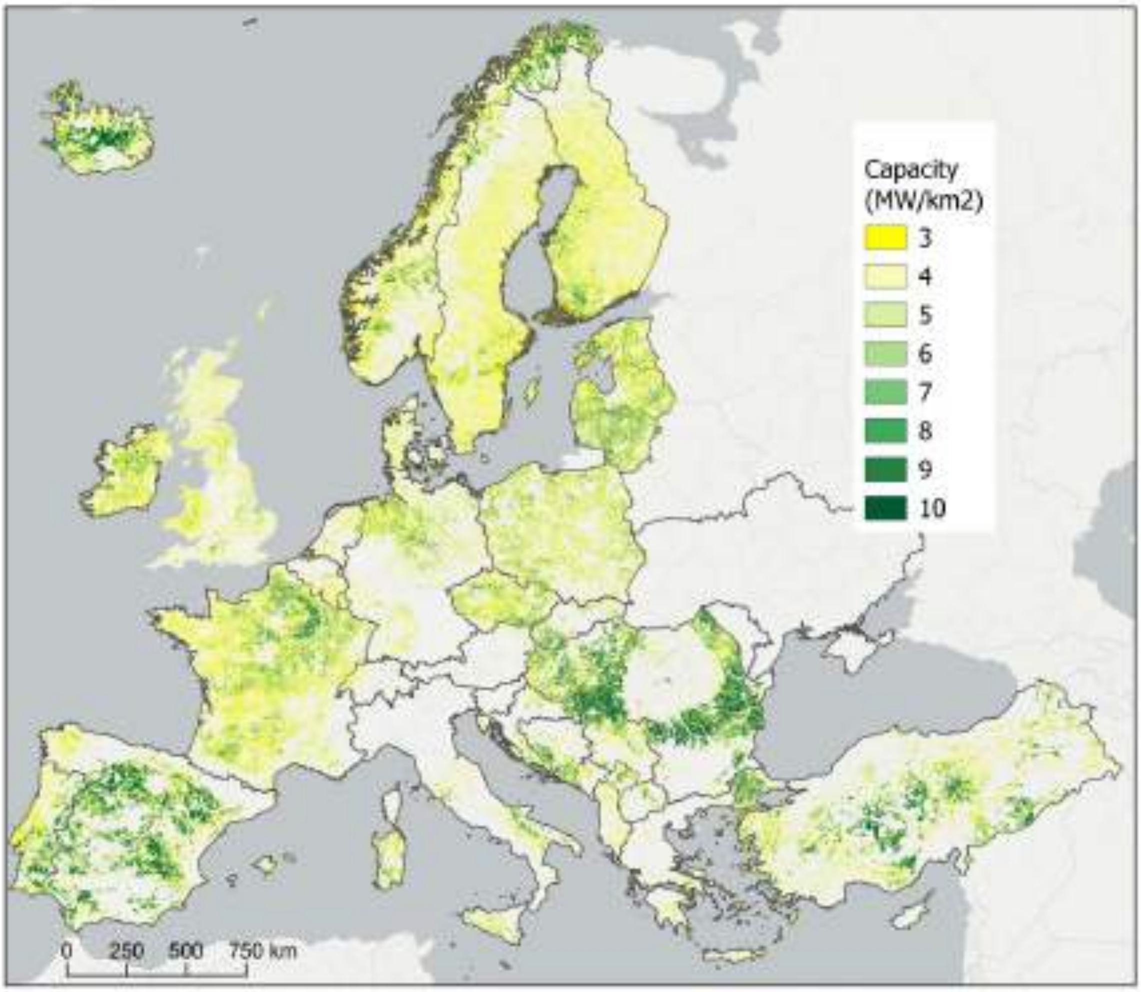

Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 13.** Onshore wind capacity potential for 2000 m setback distance



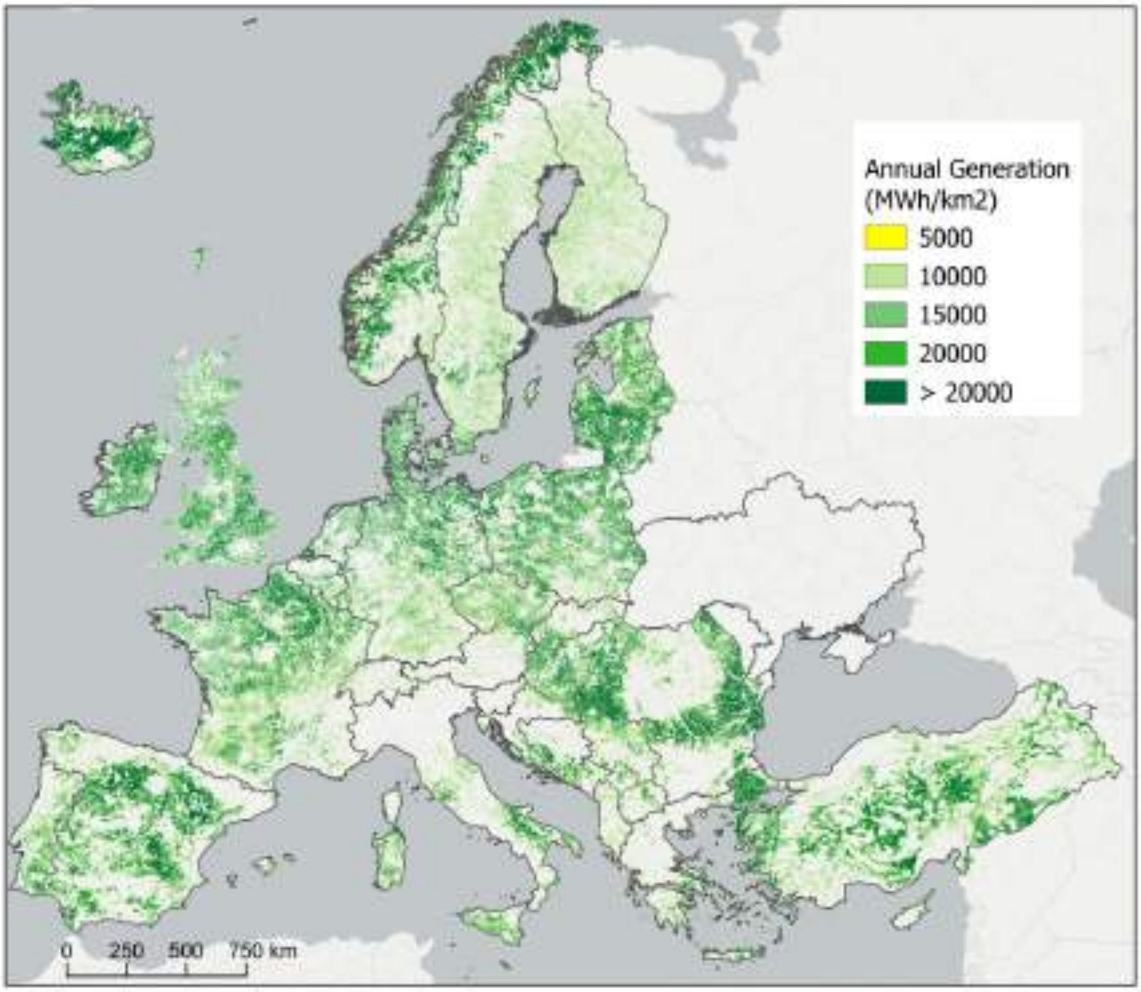

Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 14.** Onshore wind capacity potential for current setback distance regulations (reference scenario)



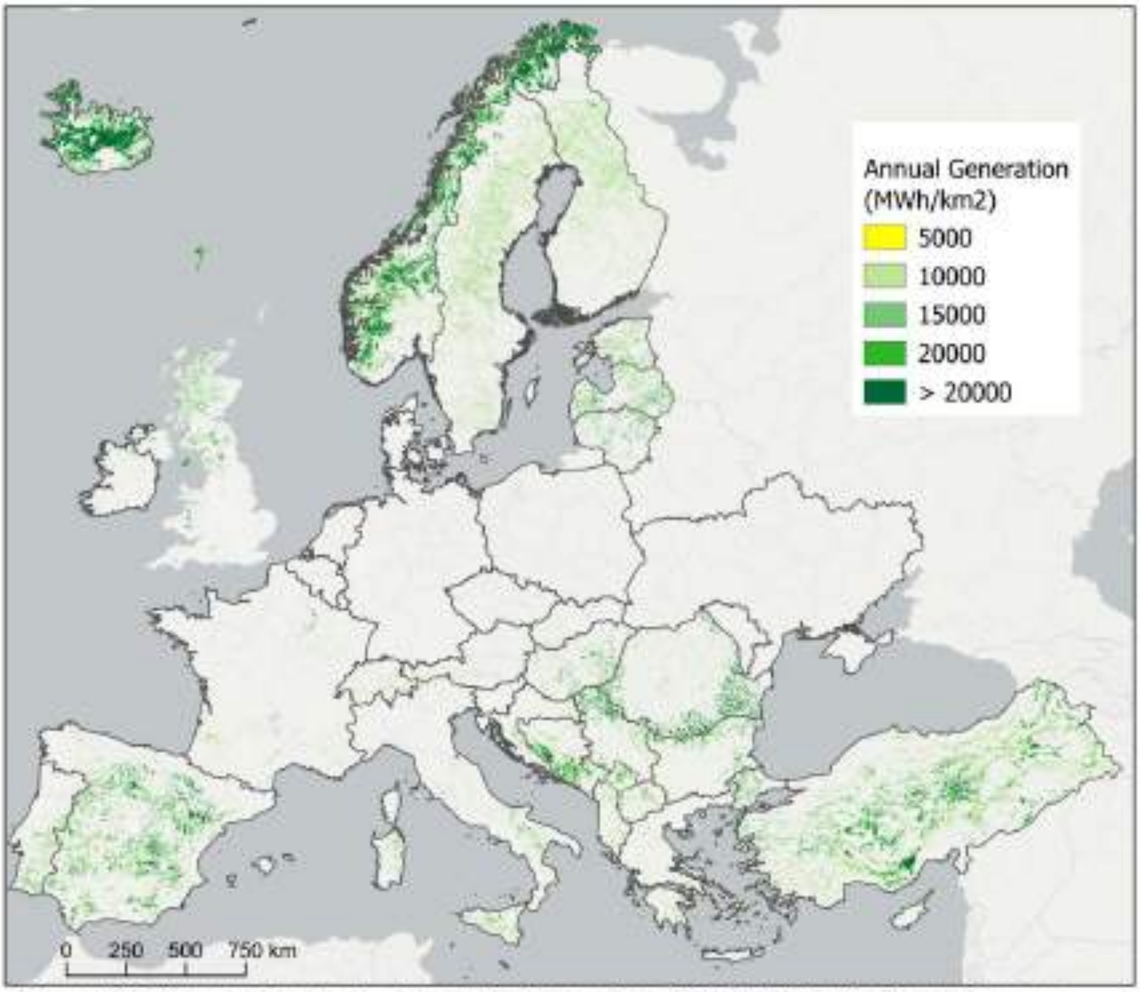

Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 15.** Onshore wind electricity generation potential for 500 m setback distance



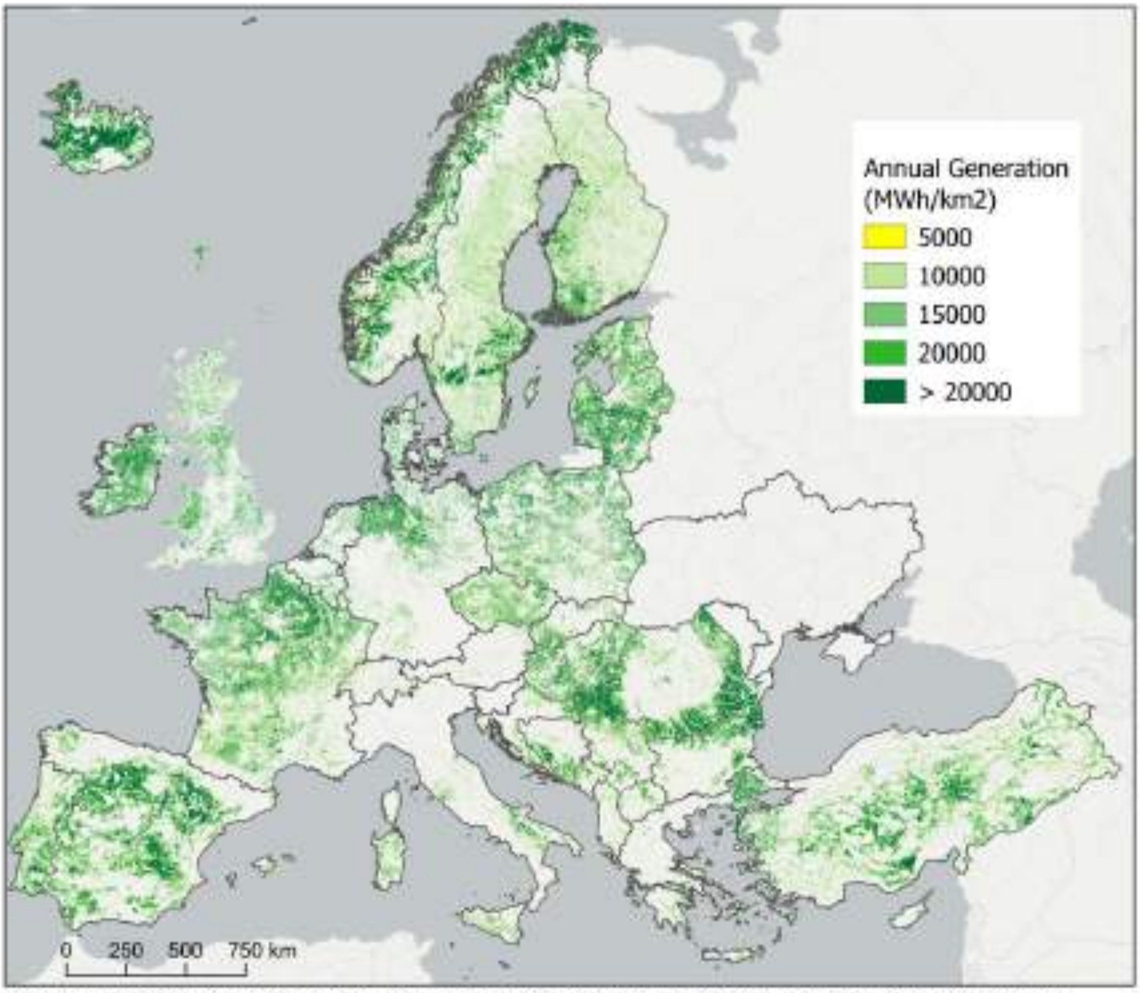

Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 16.** Onshore wind electricity generation potential for 2000 m setback distance




Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 17.** Onshore wind electricity generation potential for the reference scenario




Source: JRC/EIGL | Administrative boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

## 3.3 Results at NUTS level

The original 1 km$^2$ resolution data of ENSPRESO 2 can of course be aggregated up to larger spatial units that delineate administrative districts that are used in local, regional, and national planning activities. In the European context, the Nomenclature of territorial units for statistics, abbreviated NUTS (from the French version Nomenclature des Unités territoriales statistiques) subdivides the economic territory into regions at four different levels (NUTS O, 1, 2 and 3) , moving from larger to smaller territorial units[19].

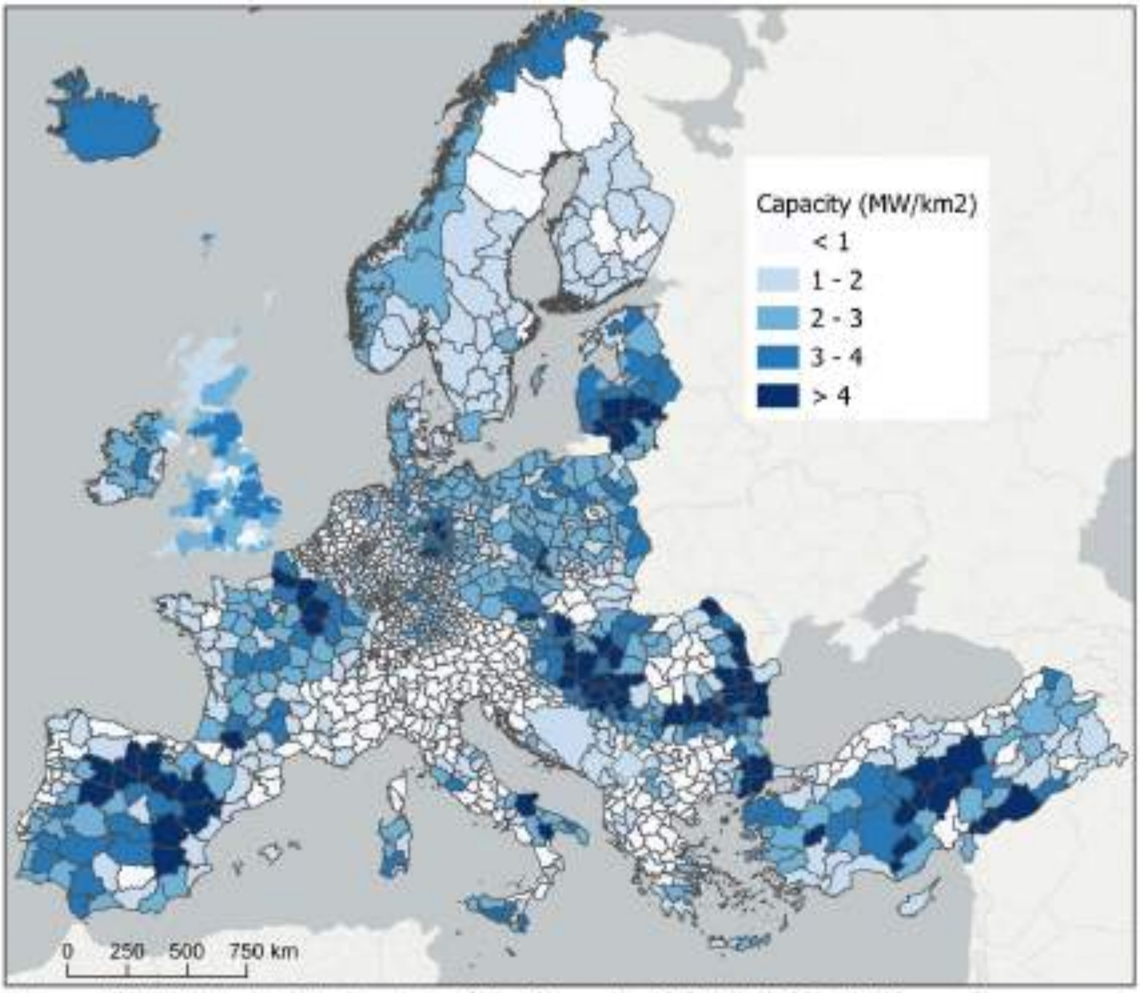
Figures 18-21 show the modelled capacity aggregated to NUTS 3 level, followed by Figures 22-25 on electricity generation. Note that the aggregation to NUTS 3 level was normalised to the size of the respective NUTS 3 areas. Figures 26 to 33 show the data aggregated to national level, but reporting non-normalised absolute data.

All full set of data that provides aggregation to all NUTS levels is available for download at the EIGL data portal[20].

[19] https://ec.europa.eu/eurostat/web/nuts

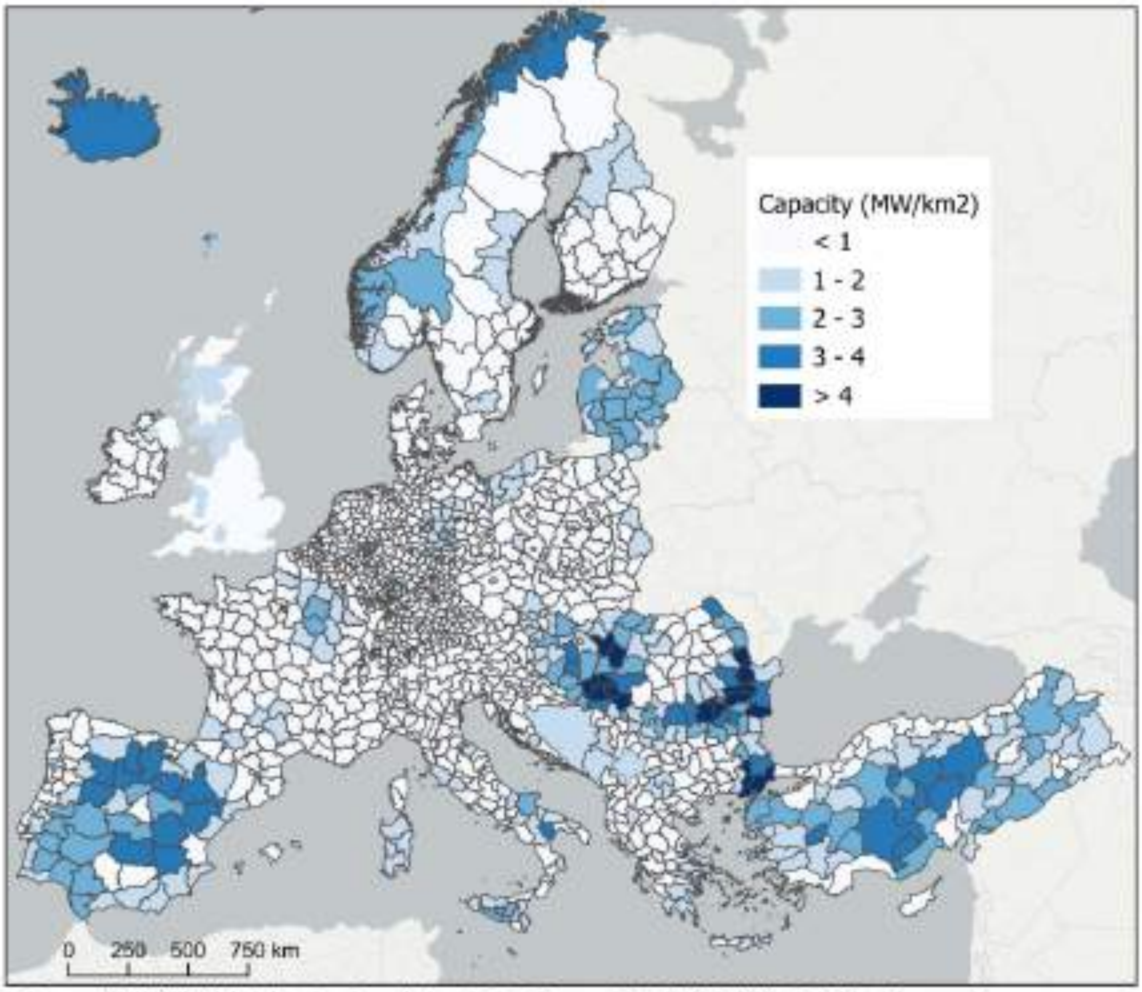
[20] https://energy-industry-geolab.jrc.ec.europa.eu/

**Figure 18.** Onshore wind capacity (MW/km2) aggregated to NUTS 3 level, 500 m setback distance



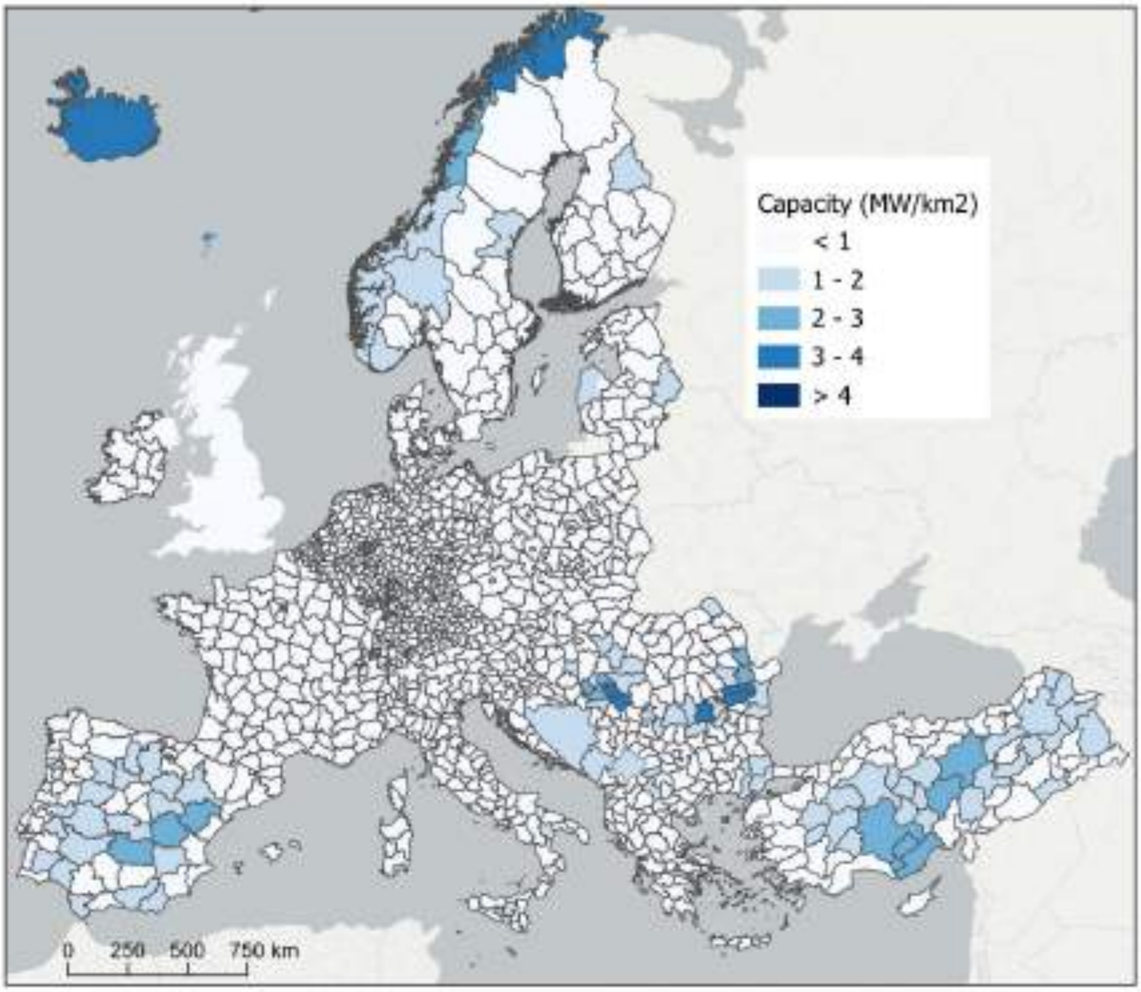

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 19.** Onshore wind capacity (MW/km2) aggregated to NUTS 3 level, 1000 m setback distance



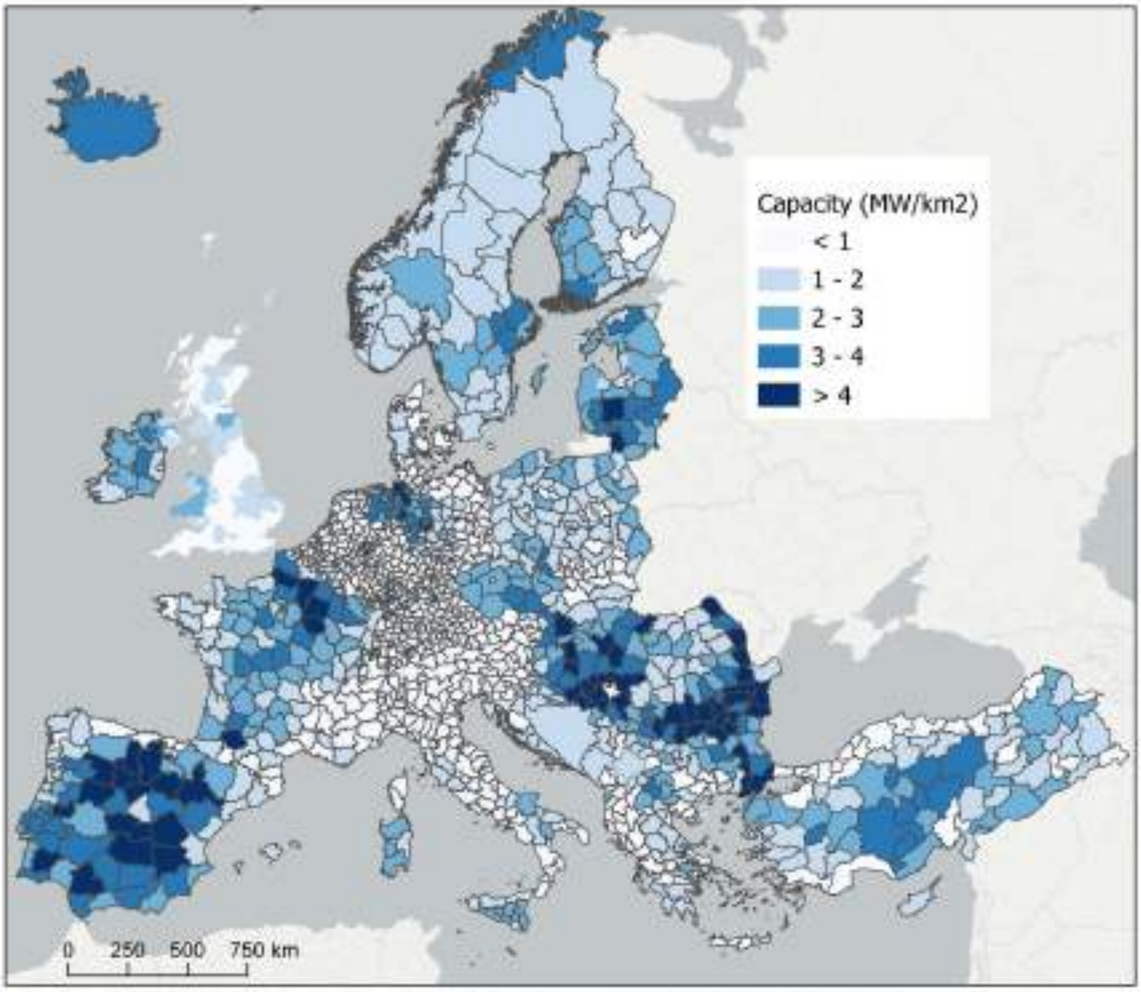

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 20.** Onshore wind capacity (MW/km2) aggregated to NUTS 3 level, 2000 m setback distance



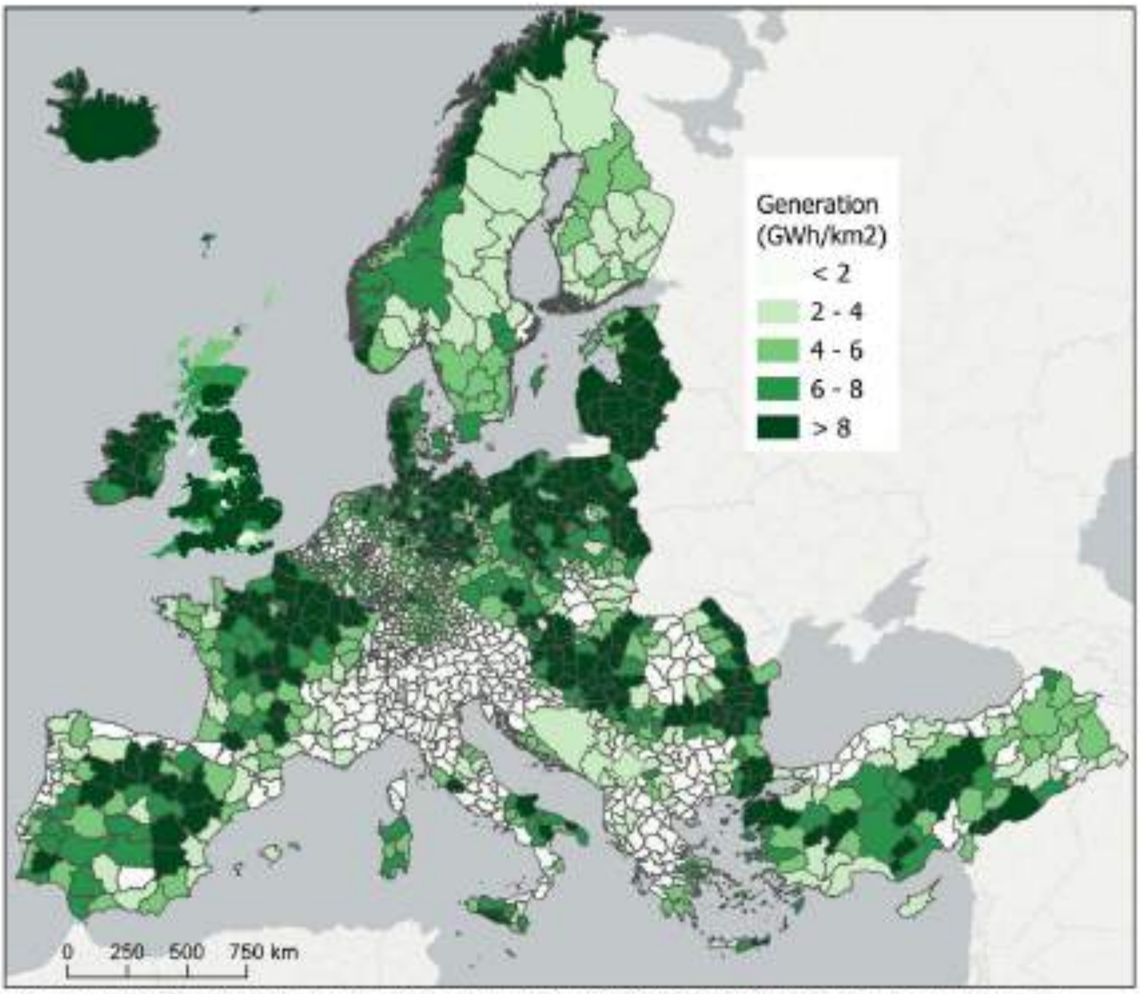

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 21.** Onshore wind capacity (MW/km2) aggregated to NUTS 3 level, reference scenario



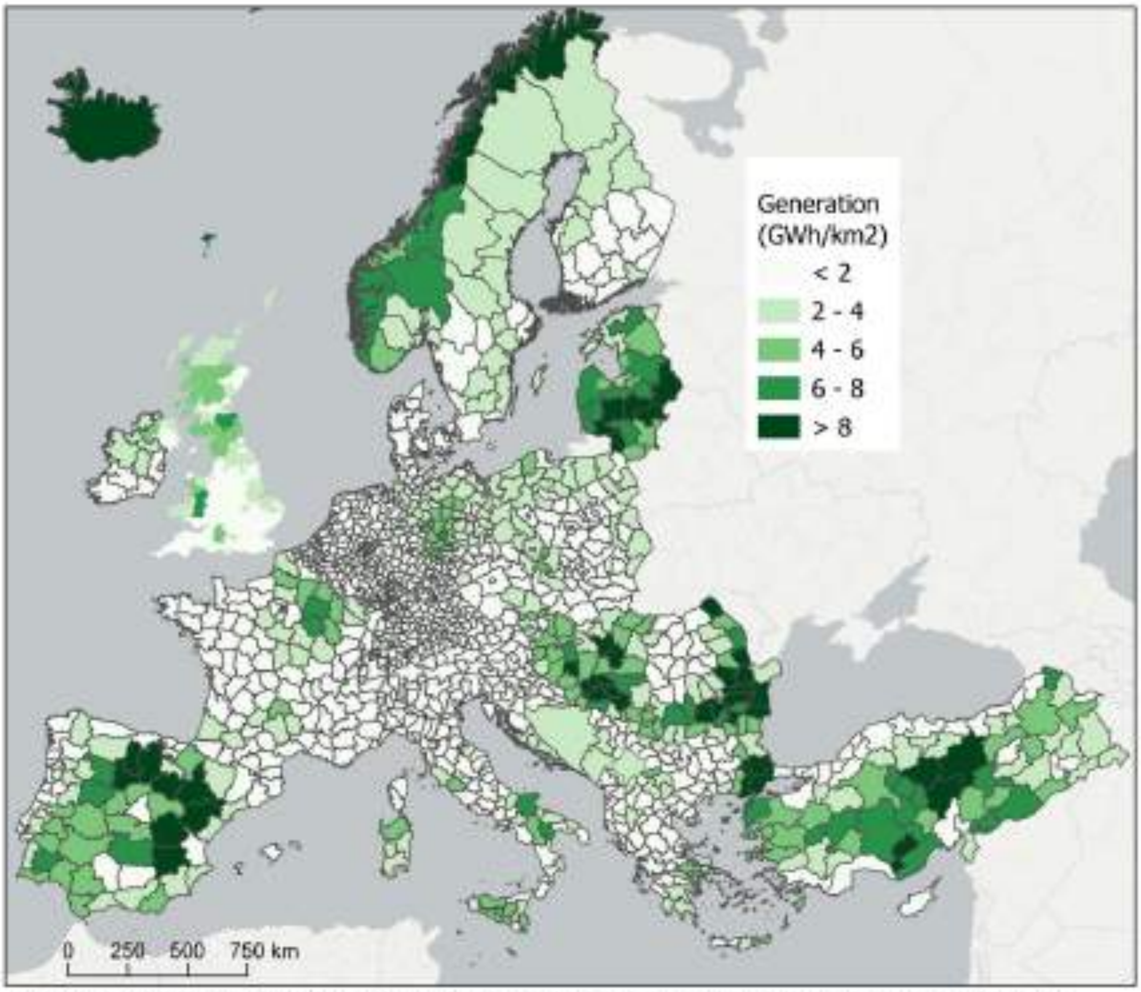

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 22.** Onshore wind generation (GWh/km2) aggregated to NUTS 3 level, 500 m setback distance



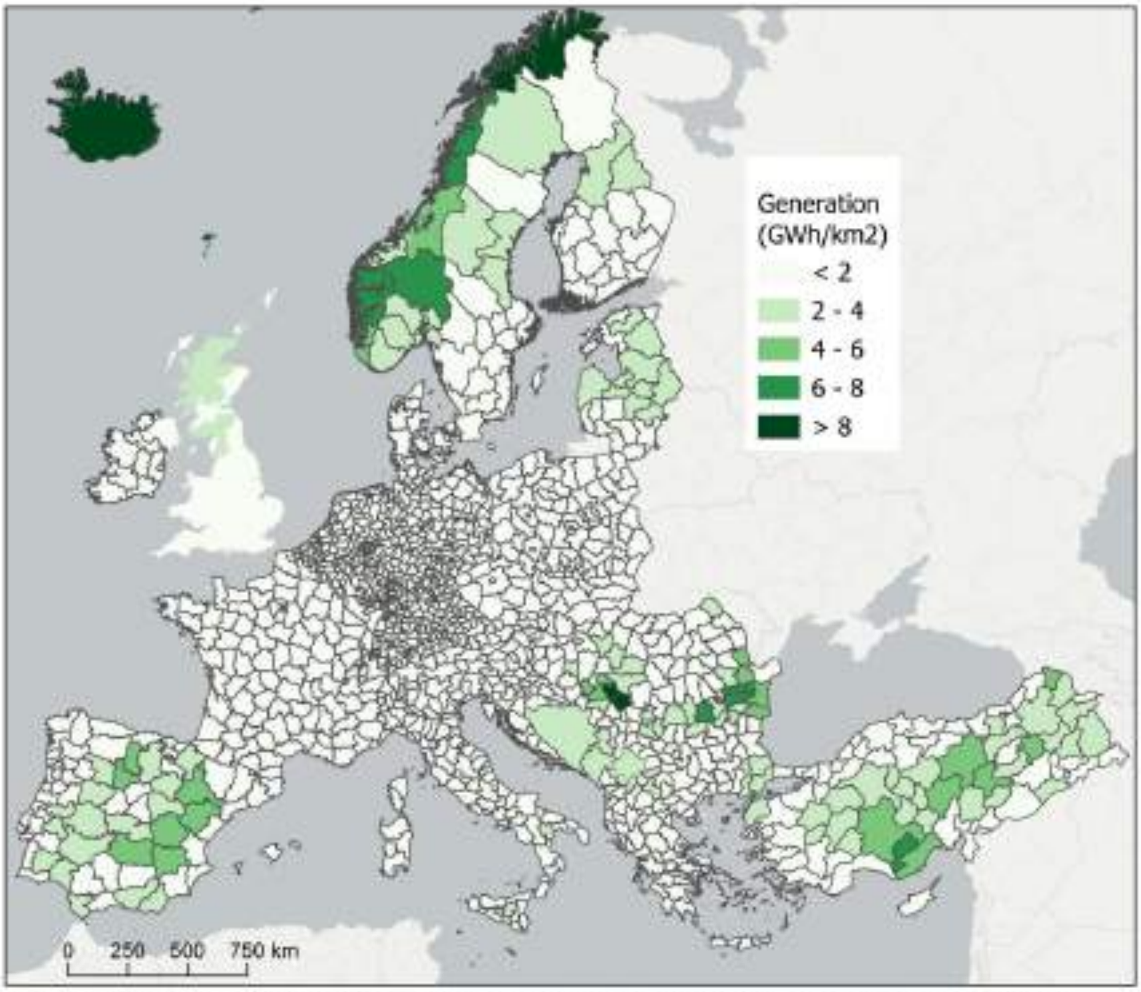

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 23.** Onshore wind generation (GWh/km2) aggregated to NUTS 3 level, 1000 m setback distance



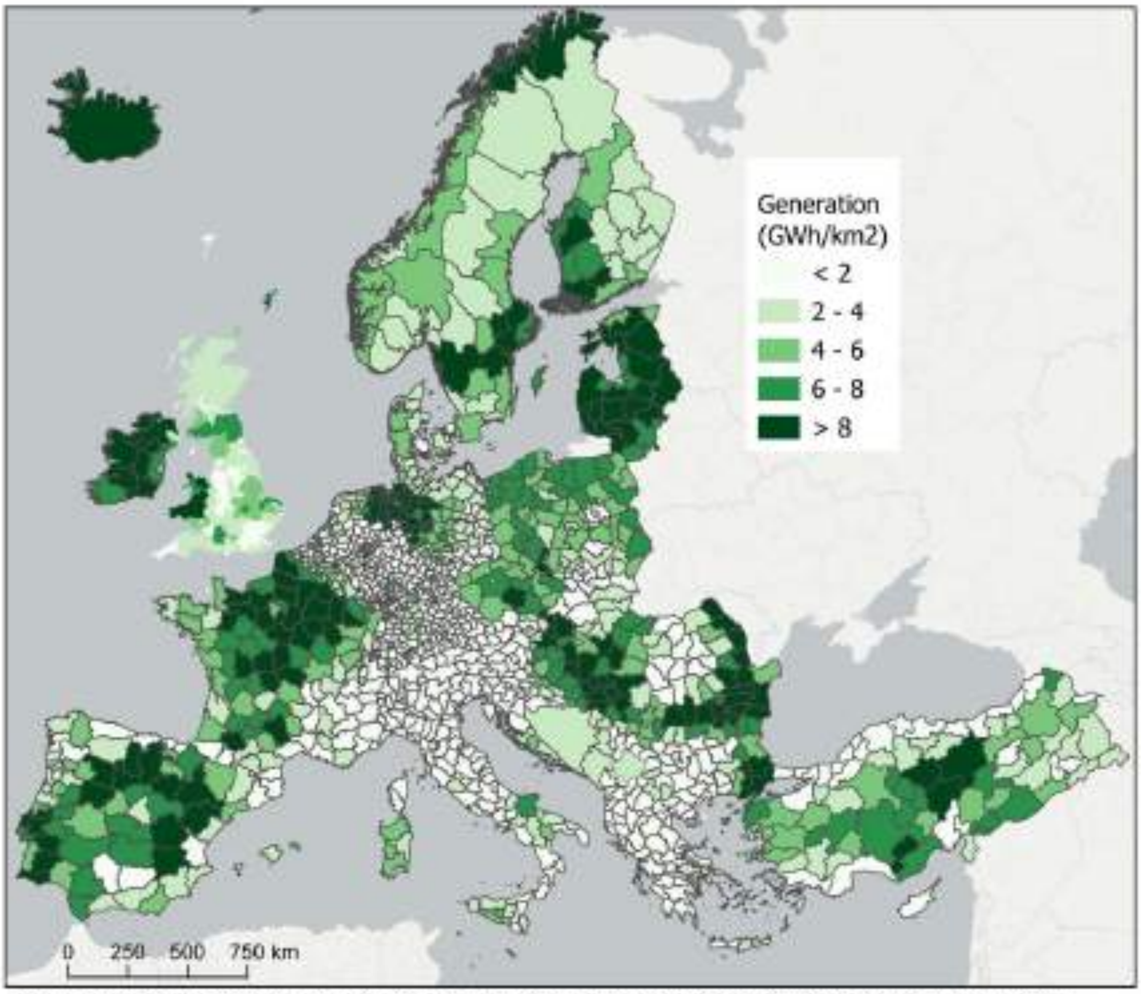

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 24.** Onshore wind generation (GWh/km2) aggregated to NUTS 3 level, 2000 m setback distance



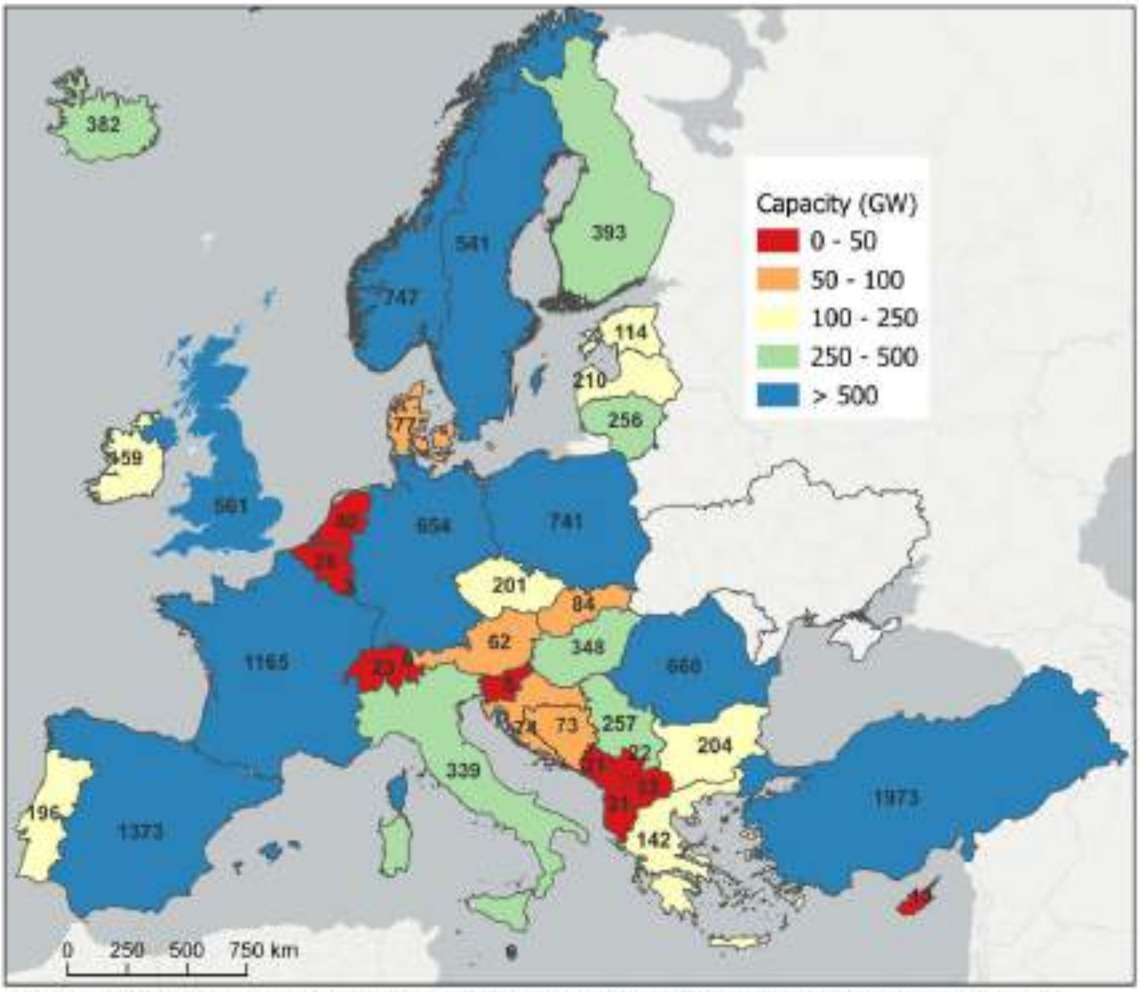

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 25.** Onshore wind generation (GWh/km2) aggregated to NUTS 3 level, reference scenario



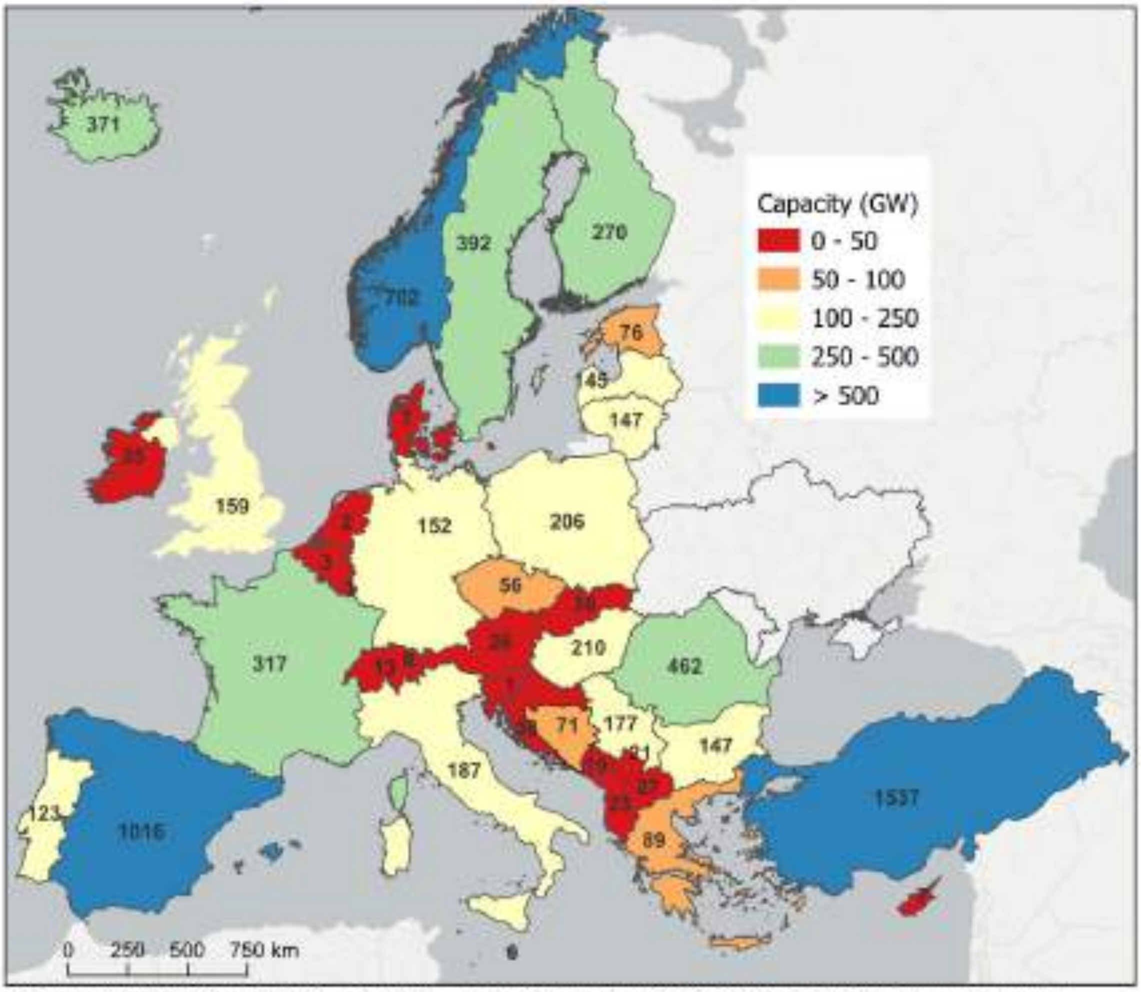

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 26.** Onshore Wind Capacity (GW) aggregated to NUTS 0 level, 500 m setback distance



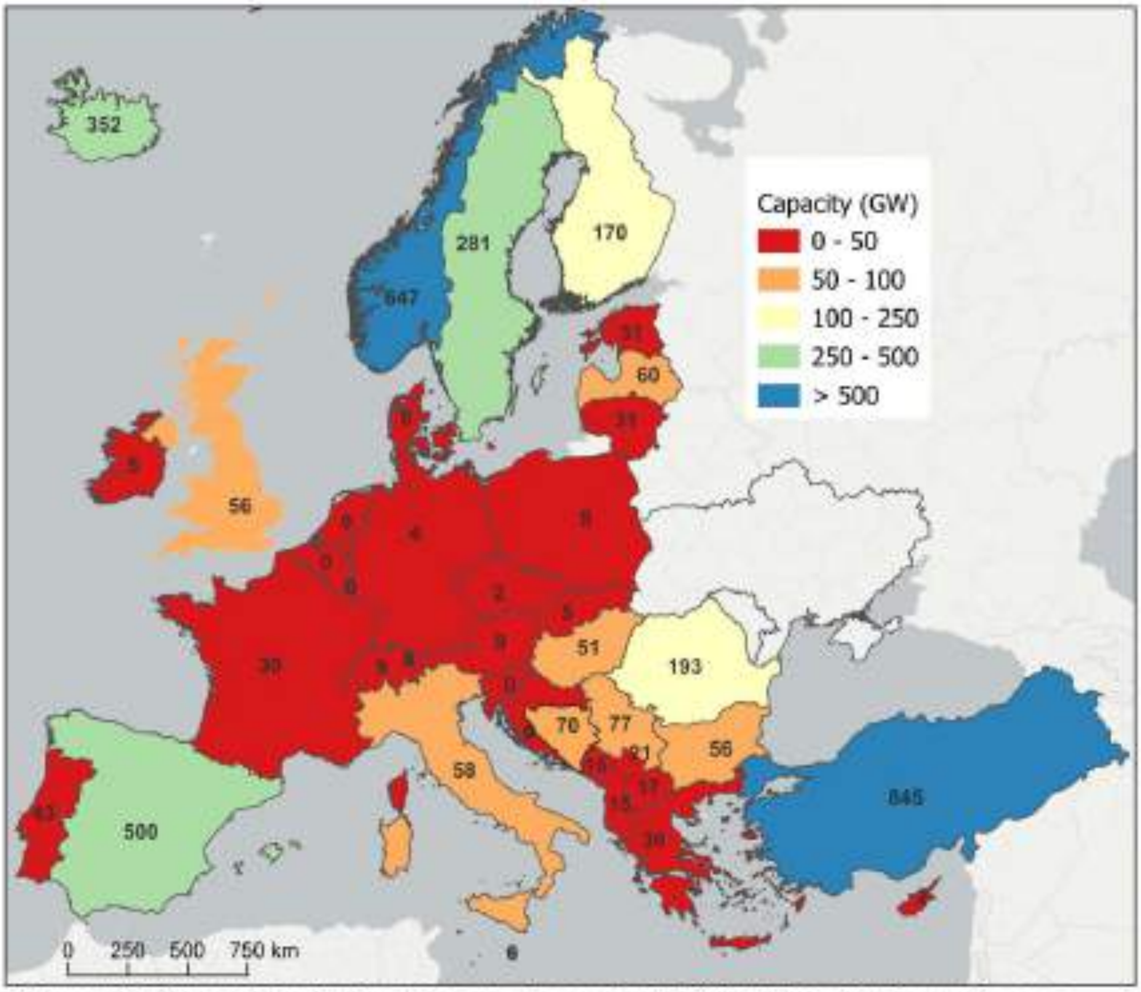

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 27.** Onshore Wind Capacity (GW) aggregated to NUTS 0 level, 1000 m setback distance



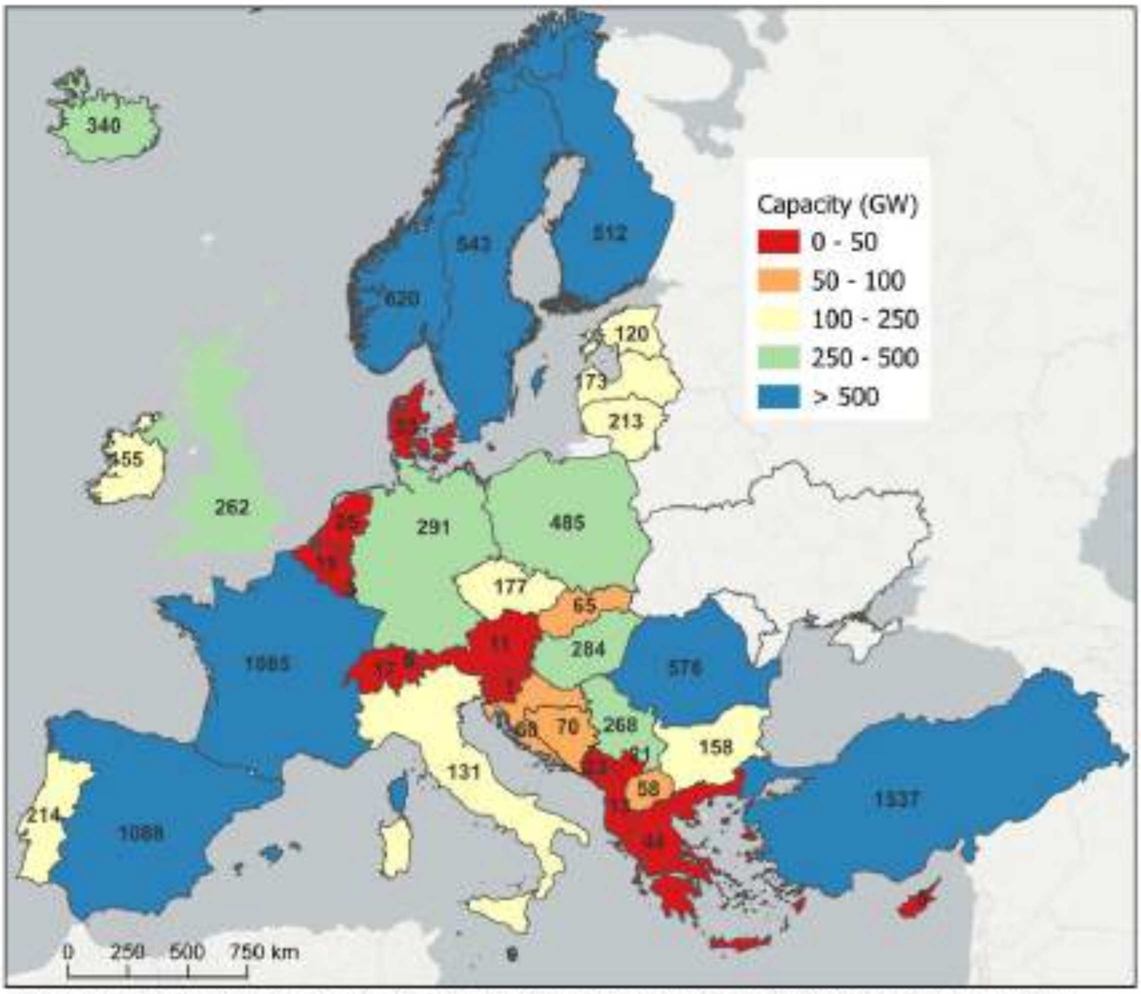

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 28.** Onshore Wind Capacity (GW) aggregated to NUTS 0 level, 2000 m setback distance



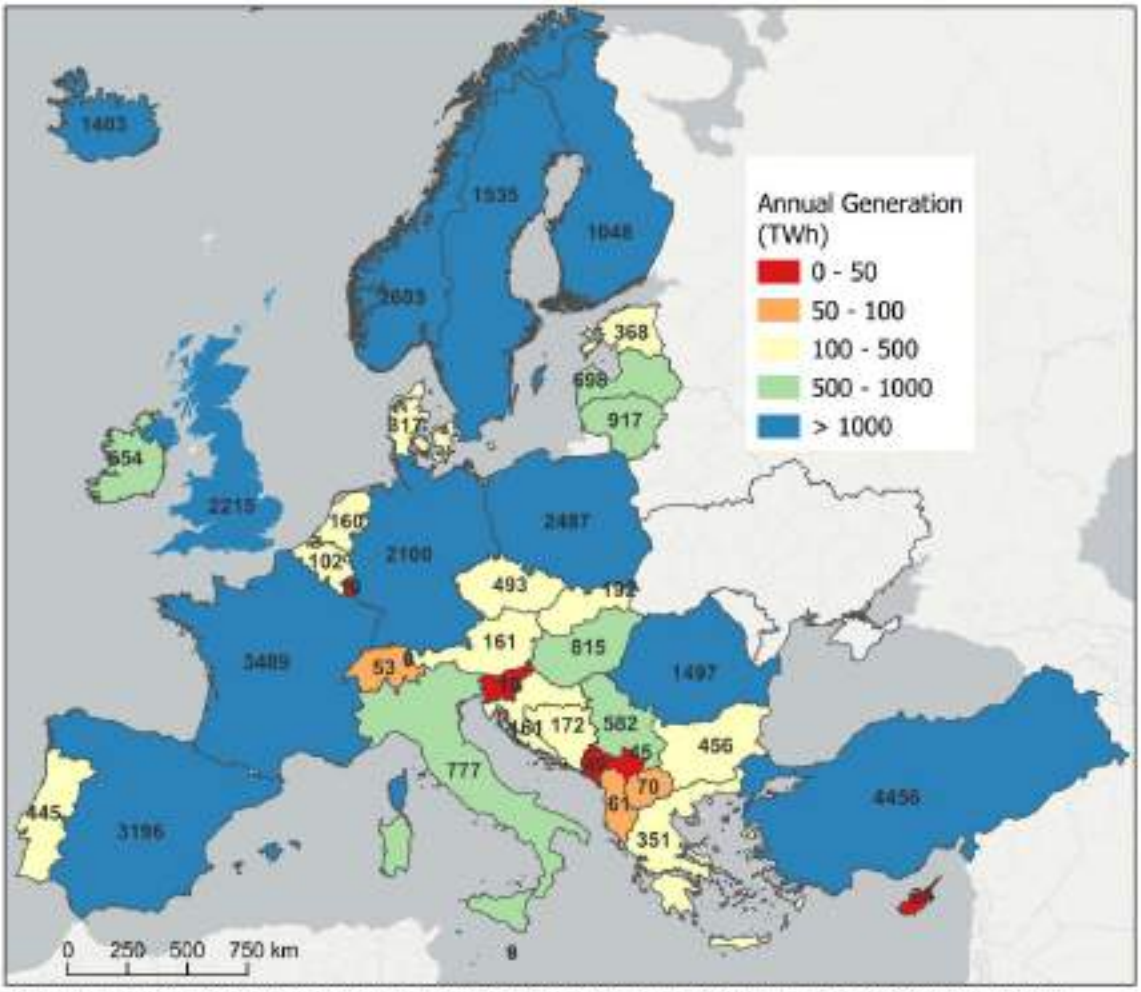

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 29.** Onshore Wind Capacity (GW) aggregated to NUTS 0 level, reference scenario



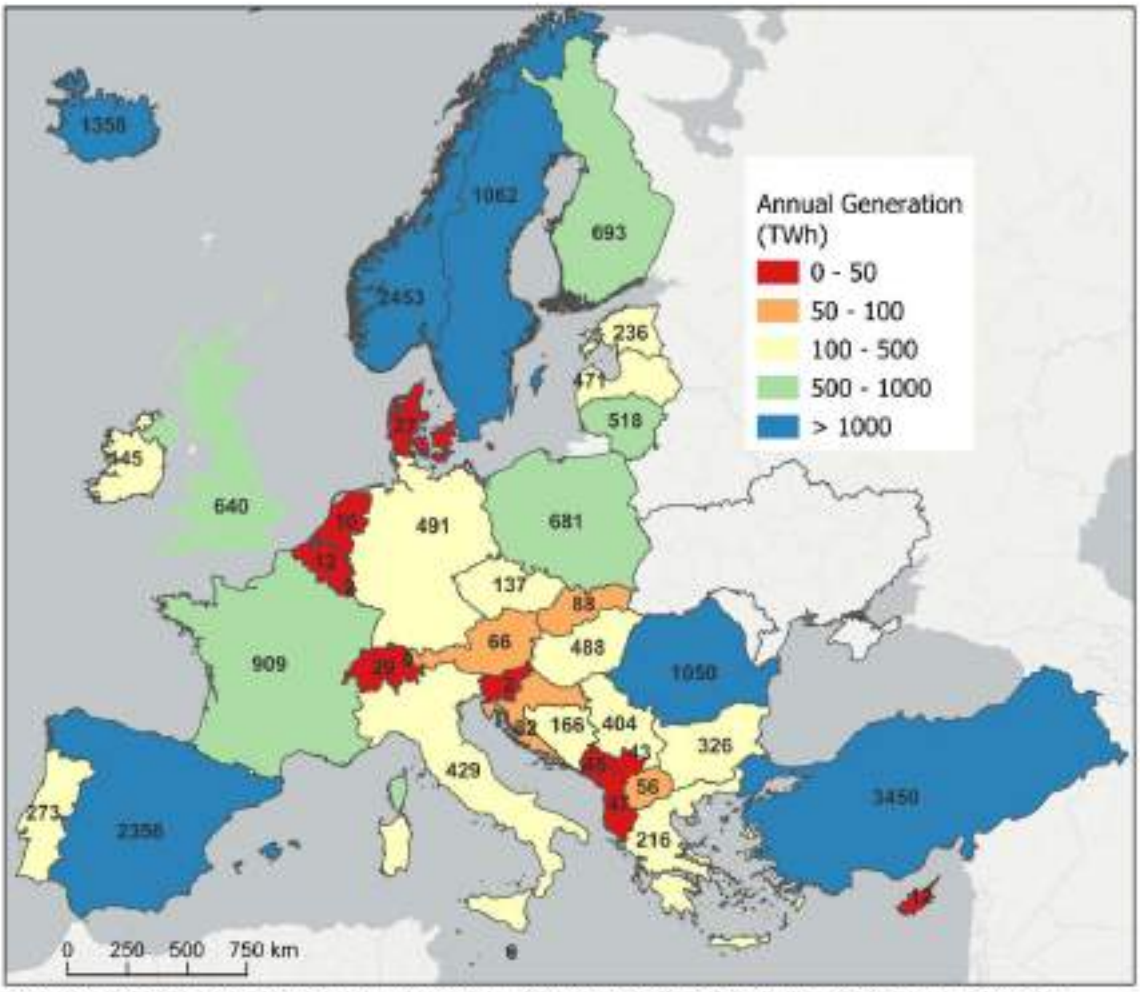

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 30.** Onshore Wind Generation (TWh) aggregated to NUTS 0 level, 500 m setback distance



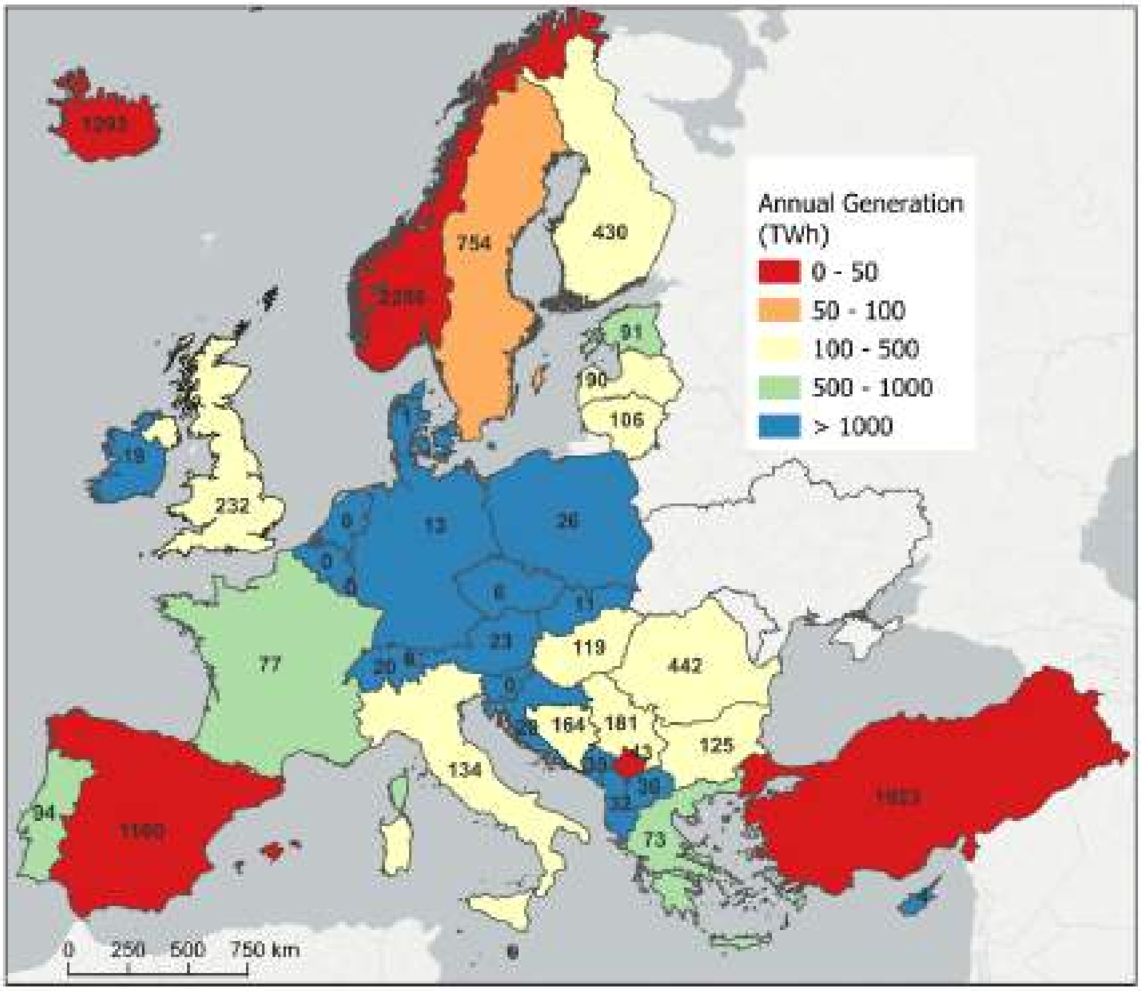

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 31.** Onshore Wind Generation (TWh) aggregated to NUTS 0 level, 1000 m setback distance



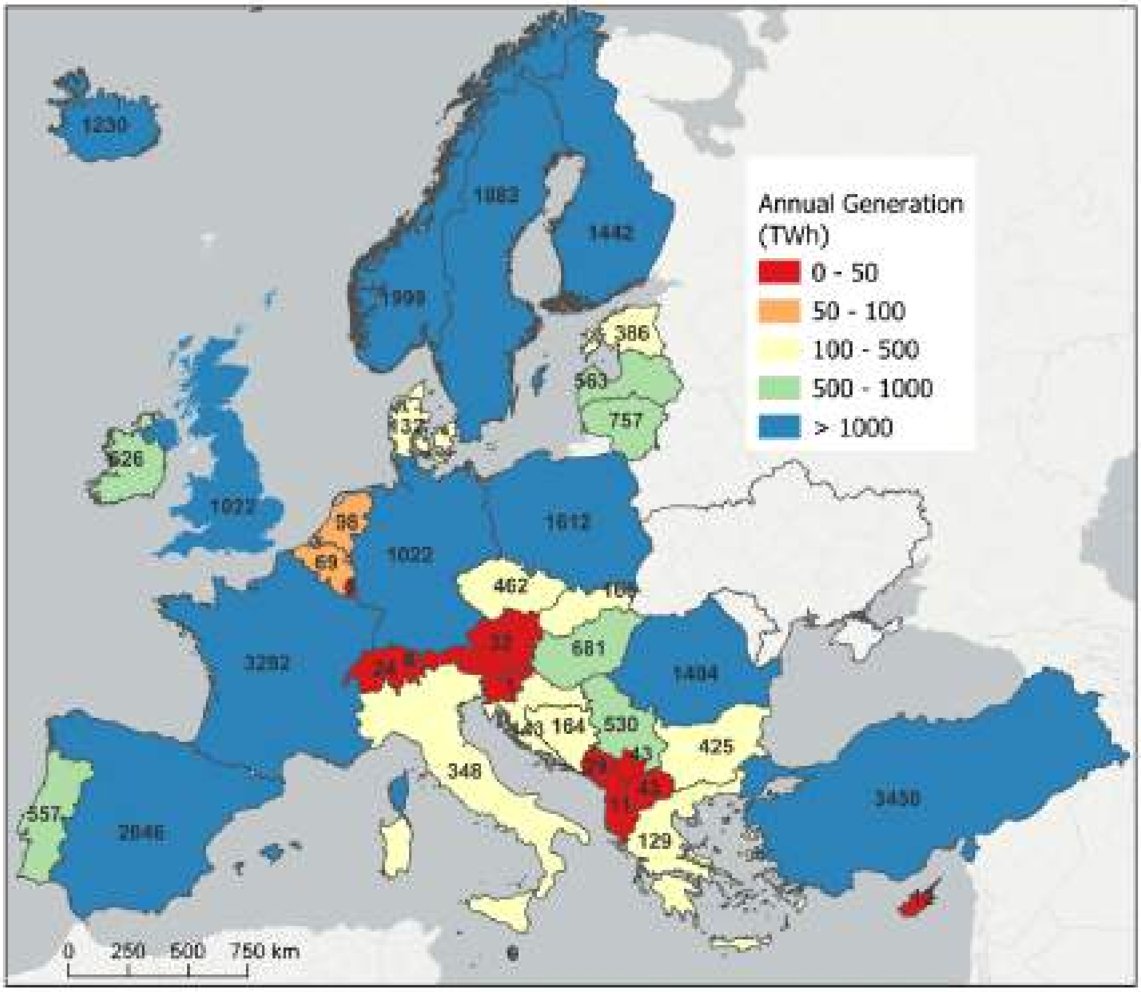

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 32.** Onshore Wind Generation (TWh) aggregated to NUTS 0 level, 2000 m setback distance




Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

**Figure 33.** Onshore Wind Generation (TWh) aggregated to NUTS 0 level, reference scenario



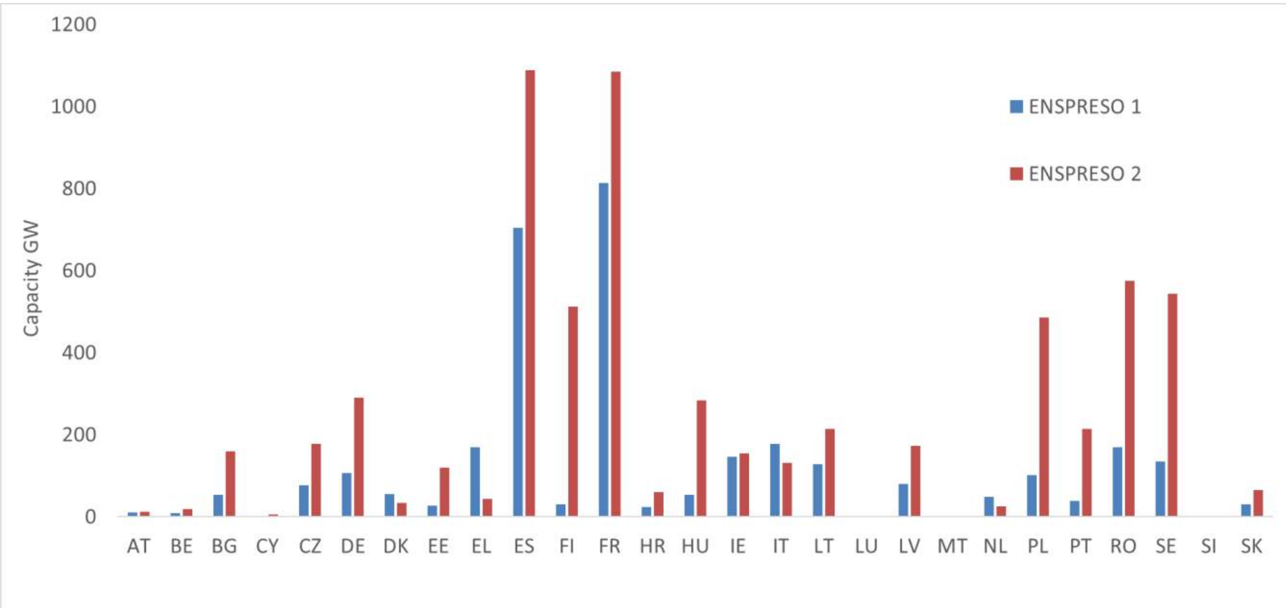

Source: JRC/EIGL | Administrative Boundaries: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO | Background Map © OpenStreetMap Contributors.

## 3.4 Comparison of the results to ENSPRESO 1

Overall, the ENSPRESO 2 project identified a substantially higher onshore wind potential compared to the original ENSPRESO 1 data. This can be exemplified by using the reference scenario results which use the actual set back distance regulations that were in the place at the time of model parameterisation. Figure 34 illustrates the differences aggregated up to member state NUTS 0 level. It can be seen that ENSPRESO 2 reports substantially higher onshore wind potential. Compared to ENSPRESO 1, many member states double the installation capacity. To a large extend this can be explained by the updated model set-up of ENSPRESO 2 that extends the maximum capacity density to 10 MW/km$^2$. In the ENSPRESO 1 model, this was limited to 5 MW/km$^2$.

There are a number of member states that record even higher differences in their potential estimates. These are mostly a function of changes in setback distance regulations, with many countries (e.g. Estonia, Poland, or Finland) relaxing their previously restrictive setback distance regulations which directly leads to higher potential estimations. The opposite example is the case of Greece and the Netherlands which have lower onshore wind potential in ENSPRESO 2 due to more restrictive setback distance regulations. Specific details on country-level results are provided in the annex of this report.

**Figure 34.** Comparison of onshore wind capacities between ENSPRESO 1 and 2, using the reference scenarios as an example. The reference scenario represents the setback distance regulations that were in place at the time both models were generated, respectively




*Source: JRC*

# 4 Conclusions

This report introduces the EU's first economically viable onshore wind energy potential at high geographical resolution (ENSPRESO 2 data set). The data provides spatially explicit information about installable wind capacity in each grid cell at a resolution of 1 $km^2$. This is complemented by estimates of the annual electricity generation if this capacity were to be installed.

ENSPRESO 2 onshore wind was generated by a detailed geographical modelling exercise which used new data sets that became available in the past decade. The model also uses updated parameterisation assumptions that reflect recent technical and methodological advances in the wind industry.

The analysis also tested the impact that setback distance regulations have on available potential by using four scenarios, with 500 m being the least restrictive and 2 000 the most conservative approach. The results show that stringent setback distances lead to a dramatic reduction of wind potential. For the 500 m scenario, an installable capacity of approximately 8 100 GW is estimated, with an associated annual electricity generation of 22 500 TWh. These figures are reduced to 4 150 GW/10 800 TWh and 1 600 GW/3 900 TWh for the 1 000 m and 2 000 m scenarios, respectively. This shows that administrative and policy decisions on setback distances have significant consequences for Europe's onshore wind energy potential.

Overall, the ENSPRESO 2 results show that the economically viable onshore wind potential is approximately double that estimated by the original ENSPRESO study in 2018. This indicates that onshore wind can play a much bigger role in the decarbonisation of Europe's energy system than previously thought.

The spatially highly resolved output of ENSPRESO 2 illustrates that the economically viable onshore wind potential is unequally distributed geographically. It is a function of a mix of drivers such as wind resource, settlement structures, and landcover types. ENSPRESO 2 data provides policymakers and energy planners with up-to-date information about this distribution and will enable more spatially informed decision making.

## References


Annoni, A., Luzet, C., Gubler, E., Ihde, J., 2001. Map Projections for Europe - EUR 20120/EN.

Blankenhorn, V., Resch, B., 2014. Determination of Suitable Areas for the Generation of Wind Energy in Germany: Potential Areas of the Present and Future. ISPRS International Journal of Geo-Information 3, 942–967. https://doi.org/10.3390/ijgi3030942

Borrmann, R., Rehfeldt, D.K., Kruse, D.D., 2020. Volllaststunden von Windenergieanlagen an Land (No. SP20004A2). Deutsche Windguard, Varel.

Bosch, J., Staffell, I., Hawkes, A.D., 2017. Temporally-explicit and spatially-resolved global onshore wind energy potentials. Energy 131, 207–217. https://doi.org/10.1016/j.energy.2017.05.052

Brovelli, M.A., Zamboni, G., 2018. A New Method for the Assessment of Spatial Accuracy and Completeness of OpenStreetMap Building Footprints. ISPRS International Journal of Geo-Information 7, 289. https://doi.org/10.3390/ijgi7080289

Brown, A., Beiter, P., Heimiller, D., Davidson, C., Denholm, P., Melius, J., Lopez, A., Hettinger, D., Mulcahy, D., Porro, G., 2016. Estimating Renewable Energy Economic Potential in the United States. Methodology and Initial Results (No. NREL/TP-6A20-64503). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1215323

COMMISSION RECOMMENDATION of 18.5.2022 on speeding up permit-granting procedures for renewable energy projects and facilitating Power Purchase Agreements, 2022.

Dalla Longa, F., Kober, T., Badger, J., Volker, P., Hoyer-Klick, C., Hidalgo Gonzalez, I., Medarac, H., Nijs, W., Politis, S., Tarvydas, D., Zucker, A., 2018. Wind potentials for EU and neighbouring countries: Input datasets for the JRC-EU-TIMES Model (No. EUR 29083 EN). Publications Office of the European Union, Luxembourg.

DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, 2023.

Enevoldsen, P., Jacobson, M.Z., 2021. Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. Energy for Sustainable Development 60, 40–51. https://doi.org/10.1016/j.esd.2020.11.004

Enevoldsen, P., Permien, F.-H., Bakhtaoui, I., Krauland, A.-K. von, Jacobson, M.Z., Xydis, G., Sovacool, B.K., Valentine, S.V., Luecht, D., Oxley, G., 2019. How much wind power potential does europe have? Examining european wind power potential with an enhanced socio-technical atlas. Energy Policy 132, 1092–1100. https://doi.org/10.1016/j.enpol.2019.06.064

European Commission. Joint Research Centre., 2021. The LUISA base map 2018: a geospatial data fusion approach to increase the detail of European land use/land cover data. Publications Office, LU.

Fields, M.J., Optis, M., Perr-Sauer, J., Todd, A., Lee, J.C., Meissner, J., Simley, E., Bodini, N., Williams, L., Sheng, S., 2021. Wind Plant Performance Prediction Benchmark Phase 1 (Technical Report). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Fingersh, L., Hand, M., Laxson, A., 2006. Wind turbine design cost and scaling model. National Renewable Energy Lab.(NREL), Golden, CO (United States).

García-Álvarez, D., Camacho Olmedo, M.T., Paegelow, M., Mas, J.F. (Eds.), 2022. Land Use Cover Datasets and Validation Tools: Validation Practices with QGIS. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-90998-7

Hoogwijk, M., de Vries, B., Turkenburg, W., 2004. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Economics 26, 889–919. https://doi.org/10.1016/j.eneco.2004.04.016

Huang, C., Yan, J., Zhang, D., Zhong, Y., 2022. Analysis of the effect of slope on the power characteristics of wind turbines in hillside terrain. Energy Reports, 2022 International Conference on the Energy Internet and Energy Interactive Technology 8, 352–361. https://doi.org/10.1016/j.egyr.2022.10.074

International Electrotechnical Commission, 2005. IEC 61400-1. Wind turbine-Part 1.

Jäger, T., McKenna, R., Fichtner, W., 2016. The feasible onshore wind energy potential in Baden-Württemberg: A bottom-up methodology considering socio-economic constraints. Renewable Energy 96, 662–675. https://doi.org/10.1016/j.renene.2016.05.013

Jung, C., Schindler, D., 2023. Reasons for the Recent Onshore Wind Capacity Factor Increase. Energies 16, 5390. https://doi.org/10.3390/en16145390

Jung, C., Schindler, D., 2022. On the influence of wind speed model resolution on the global technical wind energy potential. Renewable and Sustainable Energy Reviews 156, 112001. https://doi.org/10.1016/j.rser.2021.112001

Larsén, X.G., Davis, N., Hannesdóttir, Á., Kelly, M., Olsen, B., Floors, R., Nielsen, M., Imberger, M., 2021. Calculation of Global Atlas of Siting Parameters (Report), Calculation of Global Atlas of Siting Parameters. DTU Wind Energy, Risø, Roskilde, Denmark.

Larsén, X.G., Davis, N., Hannesdóttir, Á., Kelly, M., Svenningsen, L., Slot, R., Imberger, M., Olsen, B.T., Floors, R., 2022. The Global Atlas for Siting Parameters project: Extreme wind, turbulence, and turbine classes. Wind Energy 25, 1841–1859. https://doi.org/10.1002/we.2771

Luetkehus, I., Salecker, H., Adlunger, K., 2013. Potential of onshore wind energy. Study to the determination of the nationwide potential of space and potential of performance of the wind energy utilization at land; Potenzial der Windenergie an Land. Studie zur Ermittlung des bundesweiten Flaechen- und Leistungspotenzials der Windenergienutzung an Land.

Marconcini, M., Metz-Marconcini, A., Üreyen, S., Palacios-Lopez, D., Hanke, W., Bachofer, F., Zeidler, J., Esch, T., Gorelick, N., Kakarla, A., Paganini, M., Strano, E., 2020. Outlining where humans live, the World Settlement Footprint 2015. Sci Data 7, 242. https://doi.org/10.1038/s41597-020-00580-5

McKenna, R., Hollnaicher, S., Fichtner, W., 2014. Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany. Applied Energy 115, 103–115. https://doi.org/10.1016/j.apenergy.2013.10.030

McKenna, R., Hollnaicher, S., Ostman V. D. Leye, P., Fichtner, W., 2015. Cost-potentials for large onshore wind turbines in Europe. Energy 83, 217–229. https://doi.org/10.1016/j.energy.2015.02.016

McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C., Gruber, K., Hahmann, A.N., Jansen, M., Klingler, M., Landwehr, N., Larsén, X.G., Lilliestam, J., Pickering, B., Robinius, M., Tröndle, T., Turkovska, O., Wehrle, S., Weinand, J.M., Wohland, J., 2022. High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. Renewable Energy 182, 659–684. https://doi.org/10.1016/j.renene.2021.10.027

Merino-Martínez, R., Pieren, R., Schäffer, B., 2021. Holistic approach to wind turbine noise: From blade trailing-edge modifications to annoyance estimation. Renewable and Sustainable Energy Reviews 148, 111285. https://doi.org/10.1016/j.rser.2021.111285

Minghini, M., Frassinelli, F., 2019. OpenStreetMap history for intrinsic quality assessment: Is OSM up-to-date? Open geospatial data, softw. stand. 4, 9. https://doi.org/10.1186/s40965-019-0067-x

Miyake, S., Teske, S., Rispler, J., Feenstra, M., 2024. Solar and wind energy potential under land-resource constrained conditions in the Group of Twenty (G20). Renewable and Sustainable Energy Reviews 202, 114622. https://doi.org/10.1016/j.rser.2024.114622

Price, J., Zeyringer, M., Konadu, D., Sobral Mourão, Z., Moore, A., Sharp, E., 2018. Low carbon electricity systems for Great Britain in 2050: An energy-land-water perspective. Applied Energy 228, 928–941. https://doi.org/10.1016/j.apenergy.2018.06.127

Pryor, S.C., Barthelmie, R.J., 2024. Wind shadows impact planning of large offshore wind farms. Applied Energy 359, 122755. https://doi.org/10.1016/j.apenergy.2024.122755

Pryor, S.C., Barthelmie, R.J., Shepherd, T.J., 2021. Wind power production from very large offshore wind farms. Joule 5, 2663–2686. https://doi.org/10.1016/j.joule.2021.09.002

Riegler, G., Hennig, S., Weber, M., 2015. WorldDEM–A novel global foundation layer. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 40, 183–187.

Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B.S., Brosowski, A., Thrän, D., 2019. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energy Strategy Reviews 26, 100379. https://doi.org/10.1016/j.esr.2019.100379

Ryberg, D.S., Caglayan, D.G., Schmitt, S., Linßen, J., Stolten, D., Robinius, M., 2019. The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs. Energy 182, 1222–1238. https://doi.org/10.1016/j.energy.2019.06.052

Ryberg, D.S., Tulemat, Z., Stolten, D., Robinius, M., 2020. Uniformly constrained land eligibility for onshore European wind power. Renewable Energy 146, 921–931. https://doi.org/10.1016/j.renene.2019.06.127

Satymov, R., Bogdanov, D., Breyer, C., 2022. Global-local analysis of cost-optimal onshore wind turbine configurations considering wind classes and hub heights. Energy 256, 124629. https://doi.org/10.1016/j.energy.2022.124629

Sessarego, M., Shen, W.Z., 2020. Noise Propagation Calculations of a Wind Turbine in Complex Terrain. J. Phys.: Conf. Ser. 1452, 012063. https://doi.org/10.1088/1742-6596/1452/1/012063

Staffell, I., Green, R., 2014. How does wind farm performance decline with age? Renewable Energy 66, 775–786. https://doi.org/10.1016/j.renene.2013.10.041

van Wijk, A.J.M., Coelingh, J.P., 1993. Wind power potential in the OECD countries. Department of Science, Technology and Society, Utrecht University.

Vargas-Munoz, J.E., Srivastava, S., Tuia, D., Falcão, A.X., 2021. OpenStreetMap: Challenges and Opportunities in Machine Learning and Remote Sensing. IEEE Geoscience and Remote Sensing Magazine 9, 184–199. https://doi.org/10.1109/MGRS.2020.2994107

Wiser, R., Bolinger, M., Lantz, E., 2019. Assessing wind power operating costs in the United States: Results from a survey of wind industry experts. Renewable Energy Focus 30, 46–57. https://doi.org/10.1016/j.ref.2019.05.003

Wu, X., Hu, W., Huang, Q., Chen, C., Chen, Z., Blaabjerg, F., 2019. Optimized Placement of Onshore Wind Farms Considering Topography. Energies 12, 2944. https://doi.org/10.3390/en12152944

Zhou, Y., Luckow, P., Smith, S.J., Clarke, L., 2012. Evaluation of Global Onshore Wind Energy Potential and Generation Costs. Environ. Sci. Technol. 46, 7857–7864. https://doi.org/10.1021/es204706m

## Sources for determining regulations on setback distances for wind turbines

https://www.igwindkraft.at/fakten/?mdoc_id=1030050 (AT);
https://open.overheid.nl/documenten/ronl-0b664dbf19b17e8adeff1020970a84586e0cb213/pdf (BE, NL);
https://lex.bg/laws/ldoc/2135506117 (BG);
https://narodne-novine.nn.hr/clanci/sluzbeni/2021_12_143_2454.html (HR);
https://www.moi.gov.cy/moi/tph/tph.nsf/All/1546461946857542C225887700254B2F?OpenDocument, ΕΝΤΟΛΗ 2006_2 ΧΩΡΟΘΕΤΗΣΗ ΑΝΑΠΤΥΞΕΩΝ ΑΠΕ (CY);
http://aplikace.mvcr.cz/sbirka-zakonu/ViewFile.aspx?type=z&id=22560 (CZ);
https://eng.mst.dk/industry/noise/wind-turbines#regulationsonnoisefromwindturbines (DK);
https://www.riigiteataja.ee/akt/163756 (EE);
https://ym.fi/en/wind-power-construction (FI);
https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000033933299 (FR);
https://www.fachagentur-windenergie.de/aktuelles/detail/abstandsempfehlungen-in-den-bundeslaendern/ (DE);
https://ypen.gov.gr/wp-content/uploads/2020/11/FEK2464B_2008_RES.pdf (GR);
https://njt.hu/jogszabaly/1997-253-20-22.59#CI,
https://magyarkozlony.hu/dokumentumok/fb09f88a3bc0894ace975efc0ddfb1733aac4aa6/megtekintes (HU);
https://www.windenergyireland.com/about-wind/the-basics/wind-myths?_gl=1*ropl0u*_ga*NDA3NTg2OTY0LjE3MDEyNTgyODM.*_ga_68HVLXNSM1*MTcwMTI1ODI4My4xLjEuMTcwMTI1ODM2OC4zOC4wLjA.*_gcl_au*MTUyNjM3NDE0MC4xNzAxMjU4Mjgz (IE);
https://www.gazzettaufficiale.it/eli/id/2010/09/18/10A11230/sg;
https://delibere.regione.sardegna.it/it/visualizza_delibera.page;jsessionid=CB94BE8C159752C700D098227D0963E4.app4?contentId=DBR53435 (IT);
https://www.saeima.lv/en/news/saeima-news/31459-saeima-supports-simplified-procedure-for-construction-of-energy-supply-structures;
https://titania.saeima.lv/LIVS13/saeimalivs13.nsf/webSasaiste?OpenView&restricttocategory=1481/Lp13 (LV);
https://balticwind.eu/lithuanian-government-approves-regulations-to-accelerate-res-development/ (LT); https://today.rtl.lu/news/luxembourg/a/2049350.html (LU);
https://www.rijksoverheid.nl/onderwerpen/geluidsoverlast/vraag-en-antwoord/welke-regels-gelden-er-voor-het-plaatsen-van-windmolens-vlakbij-een-woonwijk,
https://zoek.officielebekendmakingen.nl/stb-2010-749.html (NL);
https://www.euractiv.com/section/energy-environment/news/polish-parliament-votes-700-metre-rule-for-wind-turbines/ (PL);
https://diariodarepublica.pt/dr/detalhe/declaracao-retificacao/14-a-2022-182605798 (PT);
https://legislatie.just.ro/Public/DetaliiDocument/224146 (RO);
https://www.idae.es/tecnologias/energias-renovables/plan-de-energias-renovables-2011-2020,
https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/evaluacion-ambiental/zonificacion_ambiental_energias_renovables.html (ES);
https://www.naturvardsverket.se/vagledning-och-stod/buller/buller-fran-vindkraft/ (SE)

## List of abbreviations and definitions

| Abbreviations | Definitions |
|---|---|
| AWE | Airborne Wind Energy |
| CAPEX | Capital Expenditure |
| CF | Capacity factor |
| CLC | CORINE Land Cover |
| DLR | German Space Agency |
| EEA | European Environment Agency |
| EEZ | Exclusive Economic Zone |
| EIGL | Energy and Industry Geography Laboratory |
| ENSPRESO | ENergy Systems Potential Renewable Energy SOurces |
| ESA | European Space Agency |
| GASP | Global Atlas for Siting Parameters |
| GTIF | Green Transition Information Factory |
| GWA | Global Wind Atlas |
| LCOE | levelized cost of energy |
| LUISA | Land-Use based Integrated Sustainability Assessment |
| MMU | Minimum mapping unit |
| NEWA | New European Wind Atlas |
| NUTS | Nomenclature des Unités territoriales statistiques |
| OPEX | Operational Expenditures |
| OSM | Open Street Map |

| Abbreviations | Definitions |
|---|---|
| RES | Renewable Energy Sources |
| ROI | Return of Investment |
| VGI | Volunteered Geographic Information |
| WAsP | Wind Atlas Analysis and Application Program |
| WSF | World Settlement Footprint |

## List of figures

## List of tables

## Annexes

### Annex 1. ENSPRESO 2 onshore wind capacities and annual electricity generation

**EU-27**

| NUTS ID | Onshore Wind Capacity Reference Scenario (GW) | Onshore Wind Capacity 500 m setback (GW) | Onshore Wind Capacity 1000 m setback (GW) | Onshore Wind Capacity 2000 m setback (GW) |
|---|---|---|---|---|
| AT | 11.4 | 61.81 | 25.6 | 9.6 |
| BE | 19.2 | 28.47 | 3.4 | 0.1 |
| BG | 158.8 | 204.47 | 146.7 | 56.40 |
| CY | 4.6 | 13.00 | 6.7 | 1.9 |
| CZ | 177.4 | 200.81 | 55.7 | 2.5 |
| DE | 290.6 | 654.41 | 152.4 | 4.3 |
| DK | 32.7 | 77.21 | 6.7 | 0.2 |
| EE | 120.2 | 114.08 | 75.6 | 30.5 |
| EL | 44.2 | 14 b b2.49 | 88.9 | 29.7 |
| ES | 1087.7 | 1372.99 | 1015.9 | 500.4 |
| FI | 511.6 | 392.62 | 269.5 | 169.6 |
| FR | 1085.4 | 1164.73 | 317.5 | 29.8 |
| HR | 60.1 | 74.20 | 37.7 | 9.1 |
| HU | 284.2 | 348.39 | 210 | 51.4 |
| IE | 154.5 | 159.32 | 35.1 | 4.6 |

| | | | | |
|---|---|---|---|---|
| IT | 130.6 | 338.94 | 187 | 57.8 |
| LT | 213.2 | 256.37 | 146.5 | 31 |
| LU | 2.5 | 3.43 | 0.7 | 0 |
| LV | 172.7 | 209.94 | 145 | 60.5 |
| MT | 0.01 | 0.15 | 0 | 0 |
| NL | 25 | 40.25 | 2.4 | 0.01 |
| PL | 485.3 | 741.46 | 206.1 | 8.5 |
| PT | 213.9 | 196.17 | 123.5 | 43.2 |
| RO | 575.5 | 660.01 | 462.4 | 192.6 |
| SE | 542.6 | 540.92 | 391.9 | 281.3 |
| SI | 0.6 | 5.33 | 1 | 0.07 |
| SK | 65 | 84.26 | 38.4 | 4.6 |
| **EU 27** | **6469** | **8086** | **4152** | **1579** |

## Non EU

| NUTS ID | Onshore Wind Capacity Reference Scenario (GW) | Onshore Wind Capacity 500 m setback (GW) | Onshore Wind Capacity 1000 m setback (GW) | Onshore Wind Capacity 2000 m setback (GW) |
|---|---|---|---|---|
| AL | 16.6 | 30.8 | 22.8 | 14.6 |
| BA | 69.7 | 73 | 70.6 | 69.9 |
| CH | 9.1 | 23.4 | 12.7 | 8.5 |
| FRO[21] | 5.2 | 5.27 | 5.2 | 5.2 |
| IS | 339.1 | 381.75 | 370.8 | 352.3 |
| LI | 0.00 | 0.02 | 0.02 | 0.01 |
| ME | 10.1 | 20.80 | 18.6 | 15.9 |
| MK | 15.75 | 33.22 | 26.6 | 17 |
| NO | 571.6 | 747.35 | 701.7 | 647.3 |
| RS | 215.6 | 256.53 | 176.6 | 77.4 |
| TR | 1537.44 | 1972.73 | 1537.4 | 845 |
| UK | 255.9 | 561.49 | 159.3 | 56.29 |
| XK | 20.9 | 21.8 | 21.1 | 20.9 |

[21] Faroe Islands

**EU-27**

| NUTS ID | Onshore Wind Annual Generation Reference Scenario (TWh) | Onshore Wind Annual Generation 500 m setback (TWh) | Onshore Wind Annual Generation 1000 m setback (TWh) | Onshore Wind Annual Generation 2000 m setback (TWh) |
|---|---|---|---|---|
| AT | 48.4 | 161 | 66.4 | 22.9 |
| BE | 68.7 | 102.1 | 11.9 | 0.4 |
| BG | 428.4 | 455.8 | 326.2 | 124.8 |
| CY | 12.7 | 23.9 | 12.3 | 3.5 |
| CZ | 462.6 | 492.7 | 136.6 | 6.5 |
| DE | 1022.1 | 2099.5 | 491.1 | 13.4 |
| DK | 132.2 | 316.7 | 27.2 | 0.7 |
| EE | 385.8 | 367.9 | 236 | 90.7 |
| EL | 155 | 351.4 | 216.3 | 72.7 |
| ES | 2949.8 | 3196 | 2356 | 1159.7 |
| FI | 1445.7 | 1047.8 | 693.1 | 430.2 |
| FR | 3306.8 | 3489.3 | 908.7 | 77.2 |
| HR | 146.2 | 160.7 | 82.4 | 20.3 |
| HU | 681 | 814.7 | 487.9 | 119.2 |
| IE | 629.1 | 653.8 | 144.6 | 19.2 |
| IT | 385.4 | 777.5 | 429.4 | 133.8 |
| LT | 757.8 | 917.1 | 518.1 | 106.3 |

| | | | | |
|---|---|---|---|---|
| LU | 7.3 | 10.3 | 2 | 0 |
| LV | 563.6 | 697.8 | 471.5 | 189.7 |
| MT | 0.02 | 0.4 | 0.01 | 0 |
| NL | 97.8 | 159.5 | 9.6 | 0 |
| PL | 1612.1 | 2486.7 | 680.9 | 25.8 |
| PT | 564.9 | 444.9 | 272.9 | 93.6 |
| RO | 1420.7 | 1496.7 | 1050.3 | 442.2 |
| SE | 1938 | 1535 | 1061.8 | 754.4 |
| SI | 1.3 | 10.3 | 2 | 0.2 |
| SK | 167.9 | 192.2 | 87.6 | 10.9 |
| **EU 27** | **19391** | **22462** | **10783** | **3918** |

## Non EU

| NUTS ID | Onshore Wind Annual Generation Reference Scenario (TWh) | Onshore Wind Annual Generation 500 m setback (TWh) | Onshore Wind Annual Generation 1000 m setback (TWh) | Onshore Wind Annual Generation 2000 m setback (TWh) |
|---|---|---|---|---|
| AL | 37.6 | 61.5 | 46.7 | 32 |
| BA | 165 | 172.2 | 165.9 | 164.7 |
| CH | 23.6 | 52.7 | 29.2 | 19.7 |
| FRO | 26.6 | 26.9 | 26.4 | 26.5 |
| IS | 1381.8 | 1402.9 | 1358.1 | 1292.5 |
| LI | 0.02 | 0.03 | 0.02 | 0.02 |
| ME | 43.9 | 49.4 | 44.6 | 39.1 |
| MK | 58.3 | 70.2 | 55.6 | 36 |
| NO | 2488.3 | 2603.1 | 2453 | 2285.9 |
| RS | 546.5 | 582 | 404.2 | 181.5 |
| TR | 3141.8 | 4456.2 | 3449.7 | 1922.5 |
| UK | 1096.2 | 2215.1 | 639.9 | 232 |
| XK | 42.4 | 45.1 | 42.9 | 42.3 |

## Getting in touch with the EU

### In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

### On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

## Finding information about the EU

### Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

### EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

### EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

### EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

**EU Science Hub**
Joint-research-centre.ec.europa.eu

Publications Office
of the European Union