MANUSCRIPT ACCEPTED: 13 June 2018

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Special Issue: *Climate Sciences*

REVIEW

An overview of offshore wind energy resources in Europe under present and future climate

Maite deCastro,[1] Xurxo Costoya,[2] Santiago Salvador,[1] David Carvalho,[3,4] Moncho Gómez-Gesteira,[1] Francisco Javier Sanz-Larruga,[5] and Luis Gimeno[1]

[1]Environmental PHYsics LABoratory (EPHYSLAB), Faculty of Sciences, University of Vigo, Ourense, Spain. [2]CESAM, Physics Department, University of Aveiro, Aveiro, Portugal. [3]Global Modeling and Assimilation Office (GMAO), NASA Goddard Space Flight Center, Greenbelt, Maryland. [4]Goddard Earth Sciences Technology and Research (GESTAR), Universities Space Research Association (USRA), Columbia, Maryland. [5]Coastal Observatory of the University of Coruña, Coruña, Spain

Address for correspondence: Luis Gimeno, Environmental PHYsics LABoratory (EPHYSLAB), Faculty of Sciences, University of Vigo, 32004 Ourense, Spain. l.gimeno@uvigo.es

Long-term sustainable development of European offshore wind energy requires knowledge of the best places for installing offshore wind farms. To achieve this, a good knowledge of wind resources is needed, as well as knowledge of international, European, and national regulations regarding conflict management, marine environment conservation, biodiversity protection, licensing processes, and support regimes. Such a multidisciplinary approach could help to identify areas where wind resources are abundant and where conflicts with other interests are scarce, support measures are greater, and licensing processes are streamlined. An overview of offshore wind power studies at present, and of their future projections for the 21st century, allows for determining the optimal European locations to install or maintain offshore wind farms. Only northern Europe, the northwest portion of the Iberian Peninsula, the Gulf of Lyon, the Strait of Gibraltar, and the northwest coast of Turkey show no change or increase in wind power, revealing these locations as the most suitable for installing and maintaining offshore wind farms in the future. The installation of wind farms is subject to restrictions established under international law, European law, and the domestic legal framework of each EU member state. Europe is moving toward streamlining of licensing procedures, reducing subsidies, and implementing auction systems.

Keywords: climate change; renewable energy; offshore wind farms; wind and wind power projections; legal restrictions; maritime spatial planning; licensing process; support systems; Europe

Introduction

The unprecedented increase in anthropogenic greenhouse gas (GHG) emissions driven by economic and population growth is evidence of the dominant human influence on climate change, which can be detected in atmosphere and ocean warming, changes in the water cycle, global sea-level rise, and reduced snow and ice since the mid-20th century.[1] According to the Intergovernmental Panel on Climate Change (IPCC), Assessment Report AR5, emissions were the highest in history from 2000 to 2010, producing atmospheric levels of GHG without precedent in at least 800,000 years, and leading to energy absorption by the climate system. Carbon dioxide is the largest single contributor (with increases of around 40%) to radiative forcing over 1750–2011 and its trend has increased more rapidly since 1970 than during prior decades. Economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. Although the contribution of population growth between 2000 and 2010 remained practically the same as in previous decades, the contribution of economic growth has risen sharply. To address this challenge, the Paris Agreement of 2015 (Article 2.1.a), in line with the provisions of the United Nations Framework Convention on Climate Change of 1992 and the Kyoto Protocol, set the goal of limiting the rise of average

doi: 10.1111/nyas.13924

global temperature to a maximum of 2 °C above preindustrial levels. Likewise, the European Union (EU) legislation aims to achieve a 20% reduction in GHG emissions by 2020 (and 40% by 2030) compared with the 1990 levels.

Renewable energy is crucial to achieve the international, European, and national commitments to fight climate change because they are clean and sustainable sources of energy and provide an alternative to fossil fuel combustion. In this sense, the 2030 Agenda for Sustainable Development, elaborated by the United Nations in 2015, establishes the goal of increasing the share of renewable energy in the global energy mix and ensuring and facilitating the access to affordable and clean energy by 2030, (Sustainable Development Goal 7). Renewable energy grew worldwide in the 1990s, and its growth accelerated in the 2000s, motivated by factors such as security of energy supply, resilience, industrial development, autonomy, price risks of fossil fuels, climate change, environmental sustainability, and nuclear accidents, among others. Experts have highlighted that national, regional, and local policies have played a key role in developing renewable energy markets, investments, and industry growth over the past two decades.[2] Renewable energy provided over 19.3% of global energy consumption in 2016 and continued to grow in generating capacity. The most rapid growth and the largest increases in capacity occurred in the power sector, led by solar photovoltaic (47%), wind (34%), and hydroelectric (15.5%) power.[2]

In Europe, renewable energy accounted for 85% of all new power installations in 2017—23.9 GW of a total 28.3 GW.[3] The latest reports from the WindEurope organization show that the total net European installed power capacity increased by 15.6 GW in 2017 to 933 GW, and that wind power accounted for more installations than any other form of power generation (55% of total 2017 power capacity installations). There is now 169.3 GW of installed wind power capacity: 153.5 GW onshore and 15.8 GW offshore. The year 2017 was a record year for both onshore and offshore wind installations (onshore grew 9% and offshore grew 101% compared to 2016). The total wind power installed at the end of 2017 could produce 336 TWh and covered an average 11.6% of the European electricity demand.[3] Wind energy is more widely used than ever at a time when conventional power producers burning oil, coal, and gas continue to decommission more capacity than they install. Wind power is one of the leaders in terms of installed power capacity, fast growth, and technological maturity. The latest reports from WindEurope show that wind energy remains the second largest form of power generation capacity in the EU, closely approaching gas installations. Recently, the development of wind farms has gained more strength because in recent decades, the cost of wind turbines, wind turbine maintenance, and equipment has fallen at the same time that wind turbine efficiency and availability have increased, with larger turbines intercepting higher wind speeds. Large contemporary wind turbines make electricity generation from wind farms cost-competitive with electricity from fossil fuels.[4] In particular, offshore wind power had record low bids for tenders in Denmark and the Netherlands, bringing the region's industry closer to its goal of producing offshore wind power more cheaply than coal by 2025.[3] WindEurope also shows that there are big differences between European countries in the amount of wind power installed in recent years, showing the effectiveness of policy and regulatory frameworks and the uncertainty over future energy policy in the EU. Germany remains the country with the largest installed wind capacity (56 GW), followed by Spain (23 GW), UK (19 GW), and France (14 GW). In addition, 16 European countries have more than 1 GW installed and nine of them more than 5 GW.

Europe has a total installed offshore wind capacity of 15,780 MW, which corresponds to 4149 grid-connected wind turbines across 11 countries. European offshore wind had a record net additional installed capacity of 3148 MW in 2017, which corresponds to 560 new offshore wind turbines across 17 wind farms.[5] In addition, 82 turbines, corresponding to 1927 MW, are awaiting grid connection. Fourteen offshore wind installation projects were completed in 2017, including the first floating offshore wind farm. Now, 11 projects are under construction in Germany and the UK. The total installed grid-connected capacity will be 2.9 GW once the 11 offshore projects are completed, bringing cumulative capacity to 18.7 GW. By 2020, offshore wind is projected to grow to a total installed capacity of 25 GW.[5]

Figure 1A and B show the locations of wind farms that are operational today (93) and the locations of those already under construction (18),

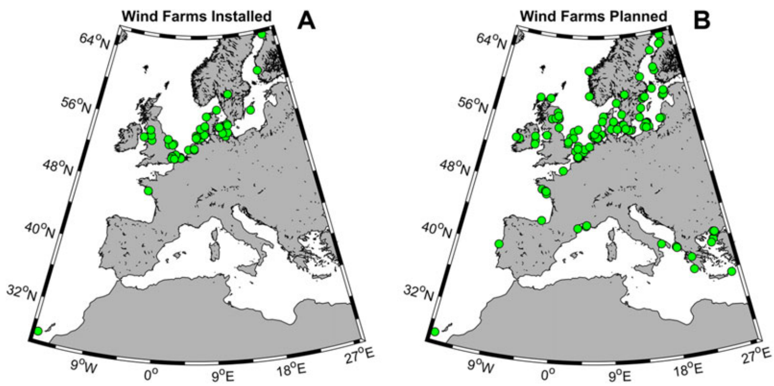

Figure 1. (A) Offshore wind farms that are operational today in Europe and (B) those already under construction, approved or planned for the following years. Data were retrieved from the Wind Power database.

approved (17), or planned (187) in Europe. Data were retrieved from the Wind Power database (https://www.thewindpower.net/), which provides information on almost 400 offshore wind farms.

The key factor in the development of wind energy projects is selecting the best locations for installation. For this purpose, it is crucial to consider both physical and legal political perspectives and to have a good knowledge of near-surface wind climate and wind resources as well as the international, European, and national regulations regarding conflict management, marine environment conservation, biodiversity protection, licensing processes, and support regimes. This multidisciplinary approach could help identify those areas where wind resources are abundant and where, at the same time, conflicts with other interests that converge in the marine environment are scarce, support measures are greater, and licensing processes are streamlined.

For these purposes, below we provide an overview of various studies of offshore wind and wind power in Europe at present and future projections for the 21st century to determine their suitability for characterizing present and future offshore wind energy resources. These studies also make it possible to determine optimal European locations to install offshore wind farms both now and during the 21st century. The results from these studies are complemented by analyses of the main international, European, and national legal frameworks governing offshore wind farm development. These analyses are described below with the aim of identifying international obligations that coastal states have to fulfill when installing and removing these devices. In addition, the EU regulations related to management of the marine space, conservation of the marine environment, and protection of biodiversity are examined. Likewise, an analysis of the domestic legal frameworks for licensing processes and financial support provided by leading European countries is also described. This multidisciplinary analysis of present and future offshore wind resources and the legal restrictions thereon can help policymakers to adopt and modify policies for long-term sustainable development of wind power in Europe.

Determination of the best locations from a physical point of view

First, wind power and wind energy estimates are described to provide an understanding of the different tools (*in situ* wind measurements, remote-sensing wind databases, reanalysis and blended wind databases, and numerical weather prediction (NWP) models) used by authors to characterize the present state of wind and wind power in Europe. Wind and power studies based on future projections throughout the 21st century are then analyzed to determine whether present offshore wind farm locations will remain adequate in the future and whether other, more suitable locations will arise because of climate change.

Wind power and wind energy resource estimates

Wind power definition and ways of estimation. Wind energy is the kinetic energy of air in motion, which is a function of mass and air velocity. The amount of power energy that is available in the wind is proportional to the cube of the wind speed (v) and to air density (ρ), which is a function that depends mainly on temperature and altitude. Air has a density of ~1.225 kg m^{-3} at sea level and 15 °C, and its density decreases with increasing altitude. In addition, two characteristics intrinsic to each turbine model play an important role: turbine radius, which determines the rotor area (A), and the rotor power coefficient (C_p), defined as a ratio of power extracted by the wind turbine to the energy available in the wind stream, which accounts for the efficiency of the wind turbine.[6,7] At this point, it is important to consider Betz's law, which states that no turbine can produce more than 16/27 (59.26%) of the kinetic energy in wind; this value is called Betz's coefficient.[8] This is a theoretical maximum, but in practice, the efficiency is lower due to frictional losses, blade surface roughness, and mechanical imperfections. Modern wind turbines operate with efficiency coefficients around 40%.[6]

Hence, the power output (usually expressed in kilowatts) generated by a turbine can be calculated according to Eq. (1):

$$P_{out} = \frac{1}{2}\rho A v^3 C_p. \quad (1)$$

Therefore, wind power production is highly dependent on wind speed. The power curve (Fig. 2) shows how large the power output will be at different wind speeds. It varies depending on each turbine model. Note that a minimum velocity, called the cut-in velocity (usually around 3 ms^{-1}), is necessary to start turbine rotation. Moreover, to avoid rotor damage, the wind turbine stops when it reaches a cut-out velocity (usually around 26 ms^{-1}). Each turbine model also has a rated wind speed, which represents the minimum wind speed at which the maximum power output is reached.

Wind speed characterization is crucial to determine the mean power delivered by a wind turbine from its power curve. This step is essential to know the wind power source and to select the best site for offshore wind farm installation. Taking into account that the power available in the wind is proportional to the cube wind speed, a region with strong, even if not constant, winds can produce more energy than a region with steady winds. Hence, mean wind speed is not always a good predictor of the wind power resource. By far, the most widely used method to characterize wind speed involves the Weibull distribution.[9–11] This is a two-parameter probability density function that represents the frequency distribution of each wind speed range for a specific period (usually 1 month or 1 year is considered). The Weibull distribution depends on two parameters: the scale parameter, which is proportional to the average wind speed, and the shape parameter, which describes the slope of the curve. Various methods have been proposed to calculate these two parameters (detailed information can be found in previous studies).[12,13] Another probability distribution function that is commonly used for wind speed characterization is the Rayleigh distribution, which is a special case of the Weibull distribution in which the shape parameter is equal to 2.

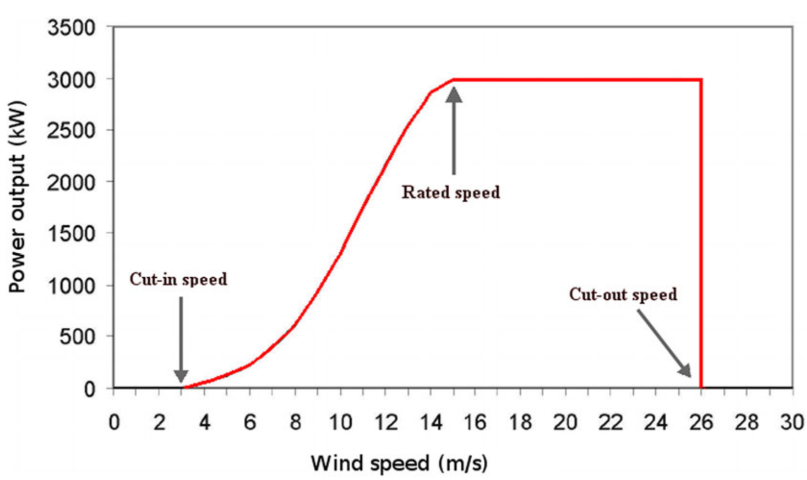

Figure 2. Power curve of the wind turbine model Vestas V90 3 MW.

To estimate the annual energy output (kWh y^{-1}) from a turbine, the Weibull distribution and the power curve must be combined. This can be done as in Eq. (2):

$$P_{mean} = \sum P_T(v)\ f(v)\,, \qquad (2)$$

where $f(v)$ is the probability of the wind speed interval v and P_T is the value of the power curve for that wind speed interval.

The energy output of a turbine is usually expressed as a capacity factor. It is a ratio of the energy generated over a time period (usually a year) to a theoretical maximum that the turbine could generate, or in other words, the amount of energy produced if the turbine had been generating at rated power all the time.

Data, models, and indices used to evaluate wind energy resources. Various data sources are used to estimate offshore wind energy resources. The choice of the best dataset is determined by the purpose of the study. Hence, *in situ* wind measurements are preferred to predict the power production of a wind farm or to establish the power curve of a wind turbine.[14] However, to evaluate wind energy resources at global or synoptic spatial scales, reanalysis datasets are needed, whereas NWP models are normally used in regional studies or even at a specific location because they can be configured to model wind with high spatial resolution. The characteristics of each of these wind data sources are analyzed below.

In situ wind databases. These databases provide a direct measure of the real situation, and therefore these are the most valuable data. The data are obtained by means of buoys (moored and drifting), vessels, floats, or wind-profiling LiDAR on platforms.[15] Traditionally, before the installation of an offshore wind farm, the wind energy potential of a given area is estimated using a mechanical anemometer installed on a mast over the ocean. To represent the wind climatology adequately, a minimum of 1 year of measurements are necessary. The main problem in collecting *in situ* data is the high cost of planning, installing, and maintaining the equipment. In addition, *in situ* wind speed observations have a very limited spatial coverage, which limits their use in regional and synoptic studies.

Wind speed observations are usually measured at 3 or 10 m, which is far below the typical hub height (around 100 m) in Europe.[16] Currently, wind turbine height varies from 50 m to more than 160 m in offshore wind farms. Therefore, wind data measured at lower heights must be extrapolated to the height at which wind turbines operate. Various statistical methods have been developed to estimate wind speed at each turbine height. To extrapolate wind speed adequately, surface roughness and atmospheric stability must also be considered. Wind profile in the boundary layer usually follows a logarithmic curve.[17] Hence, the Monin–Obukhov theory is used with the log wind profile equation:[18]

$$u_h = \frac{u_*}{k}\left\lfloor \ln\left(\frac{h}{z_0}\right) - \psi_m(\zeta) \right\rfloor\,, \qquad (3)$$

where u_h is the mean wind speed (ms^{-1}) at height h (m); u_* is the shear (or friction) velocity (ms^{-1}); k is the Von Kármán constant (~0.41); z_0 is the local roughness length (a value of 1.52×10^{-4} m over the ocean surface is usually assumed), and $\psi_m(\zeta)$ is the integrated stability function for momentum.[19–21] This last parameter depends on the Obukhov length scale, which in turn depends on surface temperature and kinematic heat flux (detailed information can be found in previous studies).[22,23]

However, in most cases, data on atmospheric stability are not collected when wind is measured. For this reason, alternative methods that discard thermal effects are normally used.[24] Assuming an atmosphere with neutral stability, wind data can be extrapolated using a logarithmic wind profile expression:[25]

$$u_h = u_{hm} * \ln\left(\frac{h}{z_0}\right) \Big/ \ln\left(\frac{h_m}{z_0}\right), \qquad (4)$$

where u_{hm} is the near-surface wind speed (ms^{-1}) and h_m is the height (m) at which near-surface wind speed is measured.

Remote-sensing wind databases. Wind speed can be obtained using various instruments onboard satellites. These instruments mainly use the microwave frequency band, which can penetrate through clouds and is more sensitive to ocean surface roughness. The roughness of the ocean surface varies depending on the relative speed and direction of the wind. In this way, it modifies the electromagnetic energy radiated by the ocean surface, in such a way that passive sensors (microwave radiometers) can calculate the brightness temperature and then, to estimate wind speed. Active sensors (scatterometers) are also used to measure wind speed. These instruments transmit microwave pulses to the ocean surface. A rougher ocean surface implies that a stronger signal returns due to the effect of capillary waves. Thus, wind speed is estimated as a function of the backscattered energy. More than a dozen satellites with microwave radiometers or scatterometers have become operational since 1987.[26,27] Table 1 lists the main datasets derived from these instruments during the 21st century. Databases that use scatterometers and the WindSat and soil moisture active passive datasets provide daily wind speed and wind direction, whereas the other databases contain only daily wind speed data. Different institutes (production institutions in Table 1) have processed data from these instruments to provide regular gridded databases. Table 1 includes the products with the highest spatial resolution and the widest temporal coverage. However, it is important to take into account that commonly there are more products for each instrument than those listed in Table 1.[27] All products are referenced to 10 m in height.[28]

The main advantage of the satellite wind data is that these datasets offer global coverage at daily temporal scale (two records per day). However, the fact that satellite-derived wind data are an indirect measurement, as commented previously, can introduce some bias. For example, heavy rain produces biases in the observations (called "rain contamination") because it artificially increases surface roughness.[29] Satellite datasets often suffer from low and insufficient spatial and temporal resolutions. They can contain data gaps due to rain contamination, instrument malfunction, or other reasons.[20] In addition, a land-masking effect has been detected in some wind satellite products, which affects the representation of near-shore ocean winds and can be relevant when analyzing wind for offshore wind energy production.[30]

Apart from scatterometers and radiometers, two other types of microwave instruments on-board satellites, altimeters and synthetic aperture radars (SARs), can be used to measure wind. These instruments have other primary purposes; therefore, their use in wind studies is not as common as those mentioned earlier.[31] The main advantage of SAR-based wind maps is that they can cover the whole coastal zone at high spatial resolution, although they provide only a few (3–5) images of a given area each month.[31,32] Envisat, launched in 2002, and Sentinel-1, launched in 2014, are the two examples of satellites operated by the European Space Agency containing SAR instruments. As for the altimeters, ERS-1&2, TOPEX/Poseidon, GEOSAT, ENVISAT, and JASON-1 are examples of satellites equipped with these instruments. Although they offer lower spatial resolution, data derived from altimeters have also been used to carry out global ocean wind speed studies.[33]

Apart from satellite-based methods, ocean wind data can also be measured remotely by means of ground-based methods. Thus, light detection and ranging (LiDAR) and sound detection and ranging (SoDAR) techniques have been tested to observe near-shore wind data in recent years.[34] Both systems are based on the Doppler-shift principle, with the difference that SoDAR emits acoustic pulses, whereas LiDAR sends out a beam of light.[35] SoDAR presents some drawbacks that reduce measurement quality. The main problem is related to dependency on temperature variation in the atmosphere. In addition, the signal-to-noise ratio is lower at high wind speeds due to background noise.[36] LiDAR systems have become more popular within the wind industry since the second half of the 2000s, mainly due to the increasing cost of using meteorological masts in deeper waters.[37,38] LiDAR can be installed on low platforms or ships, and recently the offshore wind industry has made many efforts to develop floating LiDAR systems.[39,40]

Finally, remote-sensing instruments such as SAR can be installed on the aircraft to obtain highly detailed sea-surface wind observations.[41] Costly but unmanned aerial vehicles have received more attention recently and may be used in the future to monitor marine winds.[31]

Reanalysis, analysis, and blended wind databases. Reanalysis products are datasets that combine observations and a numerical model to generate a gridded record with several atmospheric and/or oceanic variables. Such products assimilate observations from various sources: satellites, radiosondes, aircraft, buoys, ships, etc. This approach makes it possible to extend records over several decades and to obtain a global gridded dataset with a coherent physical structure.[42] Analysis datasets can also be used in wind energy applications due to the advantage that they are released in near real time.[43] However, these

Table 1. Datasets derived from satellite data

Dataset	Sensor (Satellite)	Spatial resolution	Period of time	Operator/agency	Institution
QuikSCAT	Scatterometer (QuikSCAT)	12.5 km	1999–2009	NASA, JPL	JPL, RSS, KNMI[48]
ASCAT-A	Scatterometer (MetOP-A)	12.5 km	2006–Present	ESA, EUMETSAT	KNMI, RSS[49]
ASCAT-B	Scatterometer (MetOP-B)	12.5 km	2012–Present	ESA, EUMETSAT	KNMI[50]
OSCAT-1	Scatterometer (OceanSat-2)	12.5 km	2010–2014	ISRO	ISRO, KNMI, JPL[51]
OSCAT-2	Scatterometer (ScatSat)	25 km	September 2016–Present	ISRO	KNMI[27]
RapidScat	Scatterometer (SpaceX CRS-4)	25 km	October 2014–August 2016	JPL	JPL, KNMI[52]
HY-2A	Scatterometer (HY-2A)	25 km	June 2011–Present	CNSA	NSOAS, CAST, KNMI[53]
ERS-2	Scatterometer (ERA-2)	1° × 1°	April 1995–June 2003	ESA	ESA, KNMI[54]
Aquarius	Scatterometer (SAC-D)	1° × 1°	June 2011–June 2015	CONAE, JPL, NASA	JPL[55]
WindSat	Polarimetric radiometer (Coriolis)	0.25° × 0.25°	2003–Present	USAF	RSS, NRL[56]
TMI	Microwave radiometer (TRMM)	0.25° × 0.25°	November 1997–April 2015	NASA, JAXA	RSS[57]
SMAP	Microwave radiometer (SMAP)	0.25° × 0.25°	January 2015–Present	NASA	RSS, JPL[58]
SMOS	Microwave radiometer (SMOS)	50 km	November 2009–Present	ESA	ESA[59]
AMSR-E	Microwave radiometer (Aqua)	0.25° × 0.25°	May 2002–October 2011	NASA, JPL, JAXA	RSS, JAXA[60]
AMSR-2	Microwave radiometer (GCOM-W1)	0.25° × 0.25°	May 2012–Present	NASA, JPL, JAXA	RSS, JAXA[61]
SSM/I – SSMIS	Microwave radiometer (Series of 10 satellites, F08–F18)	0.25° × 0.25°	July 1987–Present	NASA	RSS[62]
GPM GMI	Microwave radiometer (GPM)	0.25° × 0.25°	February 2014–Present	NASA, JAXA	RSS[63]

NOTE: Operator refers to the institution responsible from the launched satellite, while the production institution refers to the laboratory responsible for generating the gridded database.
Dataset abbreviations: ASCAT, Advanced Scatterometer; OSCAT, Oceansat-2 Scatterometer; HY-2A, Haiyang-2A; ERS, European Remote Sensing; TMI, Tropical Rainfall Measuring Mission's Microwave Imager; SMAP, Soil Moisture Active Passive; SMOS, Soil Moisture and Ocean Salinity; AMSR, Advanced Microwave Scanning Radiometer; SSM/I-SSMIS, Special Sensor Microwave Imager-Sounder; GPM GMI, Global Precipitation Measurement Microwave Imager. Operators abbreviations: NASA, National Aeronautics and Space Administration; JPL, Jet Propulsion Laboratory; ESA, European Space Agency; EUMETSAT, European Organisation for the Exploitation of Meteorological Satellites; ISRO, Indian Space Research Organisation; CNSA, China National Space Administration; CONAE, Argentina's National Commission on Space Activities; USAF, United States Air Force; JAXA, Japan Aerospace Exploration Agency. Production Institution abbreviations: RSS, Remote Sensing Systems; KNMI, Royal Netherlands Meteorological Institute; NSOAS, National Ocean Satellite Application Center; CAST, China Academy of Space Technology.

Table 2. Reanalysis datasets commonly used in offshore wind energy evaluation

Dataset	Type	Spatial resolution	Period of time	Vertical levels	Temporal resolution	Institution
NCEP-R2	Reanalysis	2.5° × 2.5°	1979–Present	28	6-hourly	NCEP[64]
CFSR	Reanalysis	0.5° × 0.5°	1979–Present	64	Hourly	NCEP[65]
MERRA	Reanalysis	0.5° × 0.66°	1979–Present	72	Hourly	NASA[66]
CFDDA	Reanalysis	0.4° × 0.4°	1985–2005	28	6-hourly	NCAR RDA[67]
ERA-Interim	Reanalysis	0.75° × 0.75°	1979–Present	60	6-hourly	ECMWF[68]
ERA5	Reanalysis	0.28° × 0.28°	2010–2016	137	Hourly	ECMWF[69]
JRA-55	Reanalysis	0.56° × 0.56°	1957–Present	60	6-hourly	JMA[70]
FNL	Analysis	1° × 1°	July 1999–Present	52	6-hourly	NCEP[71]
GFS	Analysis	0.5° × 0.5°	2004–Present	64	6-hourly	NCEP[72]

Dataset abbreviations: CFSR, Climate Forecast System Reanalysis; MERRA, Modern Era Retrospective Analysis for Research and Applications; CFDDA, Climate Four-Dimensional Data Assimilation; ERA, European Reanalysis; JRA-55, Japanese 55-year Reanalysis; FNL, NCEP Final Analysis; GFS, NCEP Global Forecast System. Institution abbreviations: NCEP, National Centers for Environmental Prediction; NASA, National Aeronautics and Space Administration; ECMWF, European Centre for Medium-Range Weather Forecasts; JMA, Japan Meteorological Agency.

products have the disadvantage of assimilating less data than reanalysis products.

The NASA— Global Modeling and Assimilation Office (GMAO), the European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP), and Japanese Reanalysis (JRA) laboratories have developed reanalysis databases that include wind speed and direction. Table 2 lists modern reanalysis databases that are commonly used in studies involving wind characterization. These databases continue to be updated. ERA-Interim, Climate Forecast System Reanalysis (CFSR), Modern-Era Retrospective analysis for Research and Applications (MERRA), and JRA-55 represent a new generation of reanalysis databases that is considered the third generation. However, ECMWF has already started the release of the next generation of atmospheric reanalysis products (ERA5). It is expected to be completely available in 2019, and the release is expected to cover the period from 1950 to 1978. Among other innovations, this new product will include new parameters, such as 100-m wind components, which could be of interest for analyzing offshore wind energy.

Blended wind databases are the result of combining observations from multiple satellites, in some cases including analysis data. A gridded dataset can be obtained by using an interpolation method. Table 3 shows the main features of ocean-wind blended datasets commonly used in wind energy studies.

Numerical weather prediction models. Mesoscale modeling by means of NWP models enables downscaling of reanalysis or analysis data, which increases their spatial resolution to obtain influences on wind speed at the local scale. NWP models can resolve local and regional circulation patterns and the atmospheric boundary layer, providing wind climatologies at high resolutions. They can be used over domains of several hundreds of kilometers or only a few kilometers. Their main disadvantage is related to the high computational cost required to run the models. In addition, although many efforts have been made to provide a better representation of coastal winds in mesoscale models, this remains a modeling challenge.[20] This difficulty is related to the fact that near-shore areas are affected by thermal gradients due to land–sea temperature differences and also due to local topography, which plays a key role in defining coastal wind.

Various NWP models have been used to analyze coastal winds with a focus on offshore wind energy resources. These NWP models differ in their numerical formulations and physical parameterization schemes. Some examples of NWP models used in offshore wind energy evaluation studies are Weather Research and Forecasting (WRF) model, fifth-generation Penn State/NCAR Mesoscale (MM5; Pennsylvania State University/National Center for Atmospheric Research) model, and POSEIDON or the climate model of the Consortium for Small-Scale Modeling (COSMO-CLM).[20,44–47]

Table 3. Blended sea wind datasets

Dataset	Source data	Spatial resolution	Period of time	Temporal resolution	Institution
NCDC-BSW	SSM/I, AMSR-E, TMI, QuikSCAT, and directions from NCEP/DOE2	0.25° × 0.25°	July 1987–Present	6-hourly	NOAA-NESDIS[73]
CCMP	SSM/I, AMSR-E, TRMM TMI, QuikSCAT, VOS, buoy data, ERA-40, and ECMWF analysis	0.25° × 0.25°	July 1987–Present	6-hourly	NASA[26,74]
OAFlux	NCEP, NCEP2, ERA-40, SSMI, QuikSCAT, and AMSR-E	1° × 1°	1958–2009	Daily	WHOI[75]
IFREMER-CERSAT blended wind product	ASCAT-A/B, OSCAT-1, buoy data, and ECMWF analysis	0.25° × 0.25°	November 2012–Present	6-hourly	IFREMER-CERSAT[76]

Dataset abbreviations: NCDC-BSW, National Climatic Data Center Blended Sea Winds; CCMP, Cross-Calibrated Multi-Platform; OAFlux, Objectively Analyzed Air-Sea Fluxes; CERSAT, ERS Centre for Archiving and Treatment; IFREMER, French Research Institute for Exploitation of the Sea. Production Institution abbreviations: National Oceanic and Atmospheric Administration – National Environmental Satellite, Data and Information Service; WHOI, Woods Hole Oceanographic Institution.

Studies of offshore wind and power in Europe under present climate

The optimal offshore locations for wind energy resource under present climate can be evaluated by means of regional studies based on surface wind observations and satellite-derived wind data and by means of numerical wind and wind power simulations. Most of these studies quantify the wind energy production in terms of wind power flow or wind energy density expressed in Wm^{-2}.

Several authors have analyzed wind speeds in the Black Sea region by means of surface wind observations. One year of wind measurements at 50 m a.s.l. was used to study the wind energy resource in the Turkish coastal area of Izmit, in the western Black Sea.[77] The annual average wind speed was found to be 6 ms^{-1}. Nine years of wind measurements taken at 10m a.g.l at meteorological stations in the central and eastern Black Sea region were used to determine that the annual mean wind speed ranges from 1.53 to 4.06 ms^{-1}, with the highest wind power potential found in the Sinop (wind energy density of 59.96 Wm^{-2}), Hopa, and Trabzon areas.[78] Meteorological stations in the western and central Black Sea areas were used to determine that the annual mean wind speed at 10 m a.g.l. ranged from 1.25 to 2.5 ms^{-1} from 2001 to 2010, with Sinop appearing to be the most promising region for wind energy development.[79] Wind measurements, taken at 10 m a.g.l. from meteorological stations, were also used to find that annual average wind speeds in coastal regions are 2.4 ms^{-1} for the Black Sea, 3.3 ms^{-1} for Marmara, 2.6 ms^{-1} for the Aegean Sea, and 2.5 ms^{-1} for the Mediterranean Sea.[80] Meteorological stations in the eastern Mediterranean Sea region were used to conclude that the mean wind speed at 10 m a.g.l. ranged from 0.8 to 4 ms^{-1} from 1992 to 2001. The authors further estimated the wind energy potential at 25 m a.g.l., reporting mean values of 500 Wm^{-2} at Iskenderun, Antakya, and Samandağ.[81]

Taking advantage of satellite-derived wind data, several authors have used the ocean-surface wind data from SAR to quantify offshore wind energy resources at different locations.[32,82–85] In this context, 10 m a.s.l. wind energy densities were reported to be: (1) 300–800 Wm^{-2} in the Baltic Sea; (2) 400–500 Wm^{-2} in the North Sea; (3) $>$1000 Wm^{-2} on the Norwegian west coast and in adjacent ocean areas; and (4) finally, reaching a maximum of $\sim$800 Wm^{-2} in the northwestern part of the North Sea.

Using another approach, 8 years of QuikSCAT wind measurements were used to estimate offshore wind energy resources at 10 m a.g.l. in the Mediterranean Sea, concluding that for most of it, the annual mean wind speed is between 7 and 8 ms^{-1}.[86]

The strongest winds are located in the Mistral, in the Gulf of Lyon (mean annual wind speed of 8–10 ms^{-1}), and in the Aegean Sea, and the areas east and west of Cyprus, with mean annual winds of 8–9 ms^{-1}. The offshore wind energy resources in the European seas (Mediterranean, Black, and Caspian Seas) were evaluated using 5 years of satellite-retrieved wind data.[86] The authors concluded that the windiest regions are located in the western parts of the Mediterranean and Black Seas and in the central part of the Caspian Sea, with mean wind speeds at 120 m above mean sea level between 5 and 8 ms^{-1}. Twenty years of offshore wind data from the Blended Sea Winds product, provided by the U.S. National Oceanic and Atmospheric Administration, were used to estimate offshore wind resources at 10 m a.s.l. in the Mediterranean Sea.[87] The authors found that the offshore wind power potential in the Mediterranean Sea is the highest in the Gulf of Lyon (mean annual wind power density up to ∼1600 Wm^{-2}) and the Aegean Sea (with mean annual wind power density up to ∼1150 Wm^{-2}).

Other authors have combined different wind data sources to analyze offshore wind energy resources. Offshore buoy wind measurements and QuikSCAT wind data were used to obtain offshore wind energy density values of around 250–300 Wm^{-2} at 10 m a.s.l., 500–550 Wm^{-2} at 50 m a.s.l., and 630–730 Wm^{-2} at 100 m a.s.l. in the Ionian Sea off western Greece.[88] A combination of the Envisat ASAR, ASCAT, and QuikSCAT wind data was used to determine that in eight new offshore wind farm areas in Denmark, the mean offshore wind energy density at 10 m a.s.l. ranged from 347 Wm^{-2} in Sejerøbugten to 514 Wm^{-2} at Horns.[89] QuikSCAT, NWP-modeled, and *in situ* wind measurements from the FINO-1 offshore research mast in the northern European seas were used to find average annual offshore wind energy densities of 550–650 Wm^{-2} at 10 m a.s.l.[90]

Using numerical simulation methods, wind energy resources in southeastern Europe were analyzed using 30 years (1980–2010) of NCEP/DOE AMIP-II Reanalysis (Reanalysis-2) daily averaged wind data. This simulation showed that the highest westward-propagating disturbances were found in the southern offshore European areas between Italy and Greece, with wind energy density values above 350 Wm^{-2} at 2.5 km a.s.l.[91] European offshore wind and wave energy resources were assessed using hindcast NWP simulations.[92] The authors reported that the offshore areas of northwestern Europe (latitudes > 45°), the northern part of the North Sea, and the northwestern tip of the Iberian Peninsula had the most abundant offshore wind power resources, with mean offshore wind power potential at 80 m exceeding 600 Wm^{-2}. Moreover, in the Bay of Biscay, off the coasts of Portugal and northern Spain, there is an interesting offshore wind energy resource. Offshore wind power resources in the Mediterranean Sea were evaluated using 5 years of wind data from reanalysis, reporting annual wind power densities that could reach 500–600 Wm^{-2} at 80 m a.s.l., with the most energy-rich areas located in the central parts of the Mediterranean Sea.[93]

At a more regional scale and combining different wind data sources, the offshore wind energy resource potential of the Iberian Peninsula was quantified using wind data from the QuikSCAT, ASCAT, and OSCAT scatterometers, several reanalysis databases (NCEP-R2, ERA-Interim, NCEP-CFSR, NASA-MERRA, NCEP-FNL, and NCEP-GFS), the NCDC Blended Sea Winds, the IFREMER Blended Wind Fields, the Cross Calibrated Multi-Platform (CCMP) ocean wind vectors, and a high-resolution WRF model of offshore wind data.[20,94–96] In these studies, wind energy production was assessed through the wind power flux at 10 and 120 m above sea surface level. For a height of 10 m a.s.l., the offshore areas with the highest wind power flux are located off the northwestern end of the Iberian Peninsula, reaching annual mean values in the range of 300–350 Wm^{-2}. For a height of 120 m a.s.l., the wind power flux reaches values of 500 Wm^{-2} off the northwestern end of the Iberian Peninsula and in the Strait of Gibraltar and values of 400–450 Wm^{-2} near Cape Roca and Cape St. Vincent. For the western and southern Atlantic coasts of the Iberian Peninsula, offshore wind power was also quantified through wind measurements collected at offshore buoys and several high-resolution WRF model offshore wind simulations forced by different reanalyses (NCEP-R2, ERA-Interim, NCEP-CFSR, NASA-MERRA, NCEP-FNL, and NCEP-GFS).[43,97,98] The authors reported wind energy densities at these locations (at 10 m a.s.l.) between 300 and 700 Wm^{-2}, with the highest values around Cape Finisterre, at the northwestern end of the Iberian Peninsula. Finally, the offshore wind resources of the German Bight were assessed

Table 4. Overview of offshore wind and power studies in Europe under present climate

Area	Type of wind data	Results (wind height above sea level)
Western Black Sea	*In situ*	Annual mean wind speed of 6 ms^{-1} (50 m)[77]
Middle East Black Sea	*In situ*	Characteristic wind speeds of 2–3 ms^{-1} (10 m)[78]
Middle West Black Sea	*In situ*	Annual mean wind speeds of 1.25–2.5 ms^{-1} (10 m)[79]
Turkey	*In situ*	Characteristic wind speeds of 2–3 ms^{-1} (10 m)[80]
Eastern Mediterranean Sea	*In situ*	Annual mean wind speeds up to 4 ms^{-1} (10 m)[81]
Baltic Sea	Satellite-derived (SAR)	Wind energy densities between 300 and 800 Wm^{-2} (10 m)[82]
North Sea	Satellite-derived (SAR)	Wind energy densities between 400 and 500 Wm^{-2} (10 m)[83]
Norwegian west coast ocean areas	Satellite-derived (SAR)	Wind energy densities up to 1000 Wm^{-2} (10 m)[84]
North Sea (northwestern part)	Satellite-derived (SAR)	Wind energy densities up to 800 Wm^{-2} (10 m)[85]
Mediterranean Sea	Satellite-derived (QuikSCAT)	Annual mean wind speeds of 7–10 ms^{-1} (10 m)[30]
Mediterranean, Black and Caspian Seas	Satellite-derived (AVISO)	Annual mean wind speeds of 5–8 ms^{-1} (120 m)[86]
Mediterranean and Aegean seas	Satellite and NWP (blended sea winds)	Wind energy densities up to 1200–1600 Wm^{-2} (10 m)[87]
Ionian Sea (Western Greece)	*In situ* and QuikSCAT	Wind energy densities of 630–730 Wm^{-2} (100 m)[88]
Denmark	Envisat ASAR, ASCAT, and QuikSCAT	Wind energy densities of 347–514 Wm^{-2} (10 m)[89]
Northern European Seas (Baltic and North Seas)	QuikSCAT, NWP, and *in situ*	Wind energy densities between 550 and 650 Wm^{-2} (10 m)[90]
Northern Mediterranean Sea	NWP (NCEP R2 reanalysis)	Wind energy densities up to 350 Wm^{-2} (10 m)[91]
European offshore areas	NWP	Wind energy densities up to 600 Wm^{-2} (80 m)[92]
Mediterranean Sea	NWP (ERA-Interim and NCEP reanalysis)	Wind energy densities up to 500–600 Wm^{-2} (10 m)[93]
Iberian Peninsula	Satellite, NWP, and hybrid products	Wind energy densities of 300–350 Wm^{-2} (10 m)[94]
Iberian Peninsula	Satellite, NWP, and hybrid products	Wind energy densities of 400–450 Wm^{-2} (120 m)[20,95,96]
Iberian Peninsula	NWP and *in situ*	Wind energy densities of 300–700 Wm^{-2} (10 m)[43,97,98]
North Sea	Satellite-derived (SAR)	Wind energy densities between 400 and 500 Wm^{-2} (10 m)[41]
German Bight	NWP	Annual mean wind speeds of 6–9 ms^{-1} (10–100 m)[99]

SAR, synthetic aperture radar; NWP, numerical weather prediction.

using NWP models and *in situ* wind measurements. Annual mean wind speeds ranging from 6 to 9 ms^{-1} were reported at 100 m a.s.l., with lower wind speeds closer to the coast and greater wind energy resources in further offshore locations.[99]

Table 4 summarizes all the studies just described, indicating the area under study, the type of data used, and the results obtained for wind and wind power. In addition, all the offshore locations considered to analyze wind and wind power under the present climate are summarized in the conceptual Figure 3.

Projections of offshore wind power in Europe for the 21st century

Although present offshore wind resources can be analyzed by means of meteorological observations, remote-sensing observations, or numerical models, climate models are the only tool to analyze the impact of climate change on future wind power generation. For this purpose, wind speeds from global and regional climate models (RCMs) under different GHG emission scenarios provided by the IPCC were considered. RCMs enable dynamic downscaling of wind speed simulated by global climate

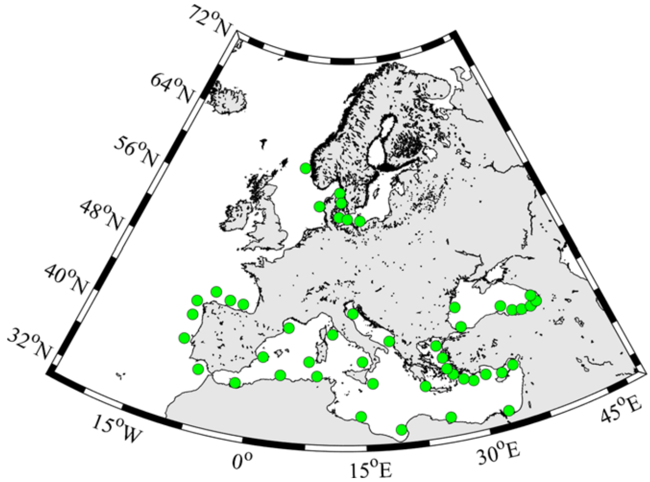

Figure 3. Conceptual map showing all the offshore locations considered to analyze wind and wind power in Europe under present climate.

models (GCMs), increasing the ease of using wind speed in localized studies. Estimating future climate change impact by means of GCMs and RCMs presents some uncertainties, which normally are dealt with by means of ensembles. An ensemble is constituted by several simulations of one or more RCMs driven by one or more GCMs under several greenhouse scenarios. Various ensembles have been developed by different European projects such as Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (PRUDENCE), ENSEMBLES, and Coordinated Regional Climate Downscaling Experiment (CORDEX). Each of these projects has improved the number of forcing GCMs, the number of ensemble members, the emission scenarios, and the spatial resolution from 50 to 25 km and then to 12.5 km in the present CORDEX project. Ensembles of GCMs were also developed under the CMIP3 and CMIP5 projects, with spatial resolutions between 100 and 210 km.

In recent decades, the impact of climate change on offshore wind power generation has been analyzed for the whole of Europe and at regional scale in the Mediterranean and Black Seas, the North Sea, the Baltic Sea, around UK, Ireland, the western Iberian Peninsula, and the Canary Islands. In this context, the impact of climate change on wind speed and wind energy density was analyzed in Europe within the framework of the PRUDENCE project.[100,101] An ensemble of one RCM (RCAO) driven by two GCMs (ECHAM4/OPYC3 and HadAM3H) under the A2 and B2 GHG scenarios was considered. When RCAO was driven by ECHAM4/OPYC3, a small increase in annual wind energy was found over northern Europe from 2071 to 2100 compared with the control period (1961–1990), with more remarkable mean wind speeds and energy densities during winter. This increment was higher under the A2 scenario. When RCAO was driven by HadAM3H, a slight decrease or no change in wind speed and wind density was found from 2071 to 2100, which shows a high degree of dependence of the RCM on GCM boundary conditions.

Future changes in extreme near-surface wind speeds in Europe were studied by means of an ensemble of eight RCMs driven by a GCM (HadAM3H) in the framework of the PRUDENCE project under the A2 scenario.[102] A possible increase in mean daily wind speed during the winter months and a decrease during autumn were found in areas influenced by North Atlantic extratropical cyclones by the end of the 21st century (2071–2100). Most of the changes in wind speeds were between 1% and 5%, which may seem small, but become significant when wind power (which varies as the cube of the wind speed) is considered.

The impact of climate change on wind energy availability over the eastern Mediterranean was analyzed by using the PRECIS regional model to perform dynamic downscaling of results obtained from HadAM3H under the A2 scenario.[103] A general decrease in wind speeds was predicted over sea areas, with a remarkable increase over the Aegean Sea from 2071 to 2100. In addition, the seasonal analysis detected a decrease in offshore wind speed during December, January, and May, and a remarkable increase over the Aegean Sea during April, August, and September.

More recently, studies on future climate projections were carried out within the framework of the ENSEMBLES project, which is the successor of the PRUDENCE project. In this sense, future extreme wind speeds and related storm loss potential were analyzed in Europe by means of 14 RCM simulations driven by seven different GCMs under the A1B scenario.[104] Two future time periods were considered, 2021–2050 and 2071–2100. An enhancement of extreme wind speeds was detected over northern parts of Central and Western Europe, with high storm loss potential in these regions, especially in Central Europe. In addition, a decrease both in extreme wind speeds and in storm loss potential was observed in Southern Europe.

Changes in wind speed, among other climate variables, were analyzed in Europe throughout the 21st century by means of 16 RCM simulations.[105] These future projections focused on 2071–2100 and were carried out by means of one RCM (RCA3) driven by seven GCMs under several scenarios (A1B, A2, B1, and B2). A wind decrease was predicted in many areas, with the exception of the northern seas and in some parts of the Mediterranean in summer. Uncertainties in future climate change related to natural variability, boundary conditions, and emissions scenarios were also found.

A weak reduction (2–6%) in the future wind power potential was detected over most of northern Europe during the next 30–40 years by downscaling coarse results from coupled GCMs under the A1B scenario from 2020 to 2049.[106] The downscaling procedure used a global stretched atmospheric model with sea surface temperature as the main forcing.

Changes in intense and extreme wind speeds over northern Europe were also analyzed by means of two RCMs (RCA3 and HIRHAM) driven by the ECHAM5 GCM under the A1B scenario.[107] Differences between two future time periods, the mid-future (2036–2065) and the end of the 21st century, and the current period (1961–1990) were analyzed. Maximum differences in energy density of approximately 15% were obtained for Northern Europe and Scandinavia, which were probably caused by the increase in cyclonic numbers and deep cyclones, especially during the cold season by the end of the 21st century.

More locally, the climate change impact on wind power development was analyzed in UK and Ireland.[108,109] For UK, it was assumed that pressure patterns are more closely related to wind climate than to GCM interpretations of surface winds.[108] In this context, geostrophic winds calculated from pressure gradients from two GCMs (ECHAM5 and HadCM3) under the A1B, A2, and B1 scenarios were used to calculate wind energy from 2081 to 2100. The authors found that although the seasonal pattern of wind speeds strengthened for most of the model-scenario combinations, the overall effect on annual wind production is likely to be smaller. A decreasing trend in geostrophic wind speed was observed from May to August under all scenarios, with a maximum (7.5%) in May under the ECHAM5 A1B scenario. All ECHAM5 scenarios showed an increase in geostrophic wind speed, ranging from 1% to 5% in September to November and from 2% to 9% in January. The HadCM3 A2 scenario continued the summer decreasing pattern (2–5%) through the autumn months, with an increase (1–4%) from January to April. They concluded that the impact of climate change on wind production was highly dependent on the scenario, the modeling process, and the empirical relationship between geostrophic wind speed and wind potential. In spite of this, ensemble runs of multiple GCMs could be appropriate. The climate change impact on wind energy resources was simulated around Ireland from 2021 to 2060 by means of the RCM RCA3 driven by the ECHAM GCM under A1B, A2, B1, and B2 scenarios.[109] The results showed a remarkable increase in the energy content of wind speed for future winter months and a decrease during the summer months.

The climate change impact on wind power generation in Europe was analyzed by means of an ensemble derived from two RCMs (COSMO CLM and REMO) driven by the ECHAM GCM under the A1B scenario from 2061 to 2100.[110] The results show that toward the end of the 21st century, projected annual average wind energy densities will experience significant changes across Europe, developing remarkably stronger seasonal patterns. An increase in wind potential is projected over Northern and Central Europe, especially in winter and autumn, and a decrease over Southern Europe in all seasons with the exception of the Aegean Sea. The Aegean Sea is likely to experience an increment in annual wind energy from increases in summer and autumn.

The projected changes in the 50-year return wind speeds and associated uncertainties were investigated by four RCM simulations driven by two GCMs (BCM and ECHAM5) downscaled with two RCMs (HIRHAM5 and RCA3) under the A1B scenario from 2070 to 2099.[111] The results show a projected change in wind of less than 2 ms^{-1}. The largest source of uncertainty is the intermodel spread, with differences in 50-year return wind of over 20 ms^{-1} at some locations between two different downscalings.

At a more regional scale, the offshore wind power potential and its future trend were assessed in the Baltic Sea near the Latvian coast by means of the CLM RCM driven by the HadCM3 GCM under the A1B scenario from 2012–2051 and 2071–2100.[47] The results indicate no significant changes in average wind speed or in the interannual variability of annual and monthly wind speed for the two future time periods compared with 1981–2010. These results suggest that wind energy resources will not change significantly over the 21st century and will continue to be a stable resource for electricity generation. The impact of climate change on wind energy resources was also simulated over Ireland from 2021 to 2060 by means of the RCM COSMO-CLM driven by the ECHAM GCM under the A1B and B1 scenarios.[112] This study continued previous research that used the RCA3 RCM.[109] Results projected remarkable increases in 60-m wind speed during winter and decreases during summer. These results are in accordance with the results obtained from the RCA3 RCM, increasing confidence in the robustness of such projections.

Future changes in wind potential over Europe were assessed using an ensemble of 15 regional simulations carried out by means of 10 RCMs driven by six GCMs under the A1B scenario for two future time periods, 2031–2060 and 2071–2100.[113] They show with a high confidence level that changes in wind power potential will remain within ±15% and ±20% by mid- and late-century over most of Europe. In addition, a decreasing trend over the Mediterranean areas and an increase over Northern Europe were also predicted.

The climate change impact on large-scale winds in the southern North Sea region was analyzed by means of an ensemble of eight RCM simulations carried out with the RACMO2 RCM driven by the EC-Earth GCM under the RCP8.5 scenario within the framework of the CORDEX project.[114] The main conclusion was that global warming will not change the wind climate beyond the natural climate variability experienced in the past.

A statistical-dynamic downscaling approach was proposed to analyze both present wind energy output and long-term climate projections in Europe by means of the ECHAM GCM under scenarios A1B, A2, and B1.[115] Results are in accordance with previous studies in the area under study, showing an increase in wind energy output over Northern Europe and a negative trend over Southern Europe. This study was later expanded using an ensemble of the COSMO-CLM RCM driven by 22 GCMs from the CMIP5 project under the RCP4.5 and RCP8.5 scenarios for two future time periods, 2021–2060 and 2061–2100 within the framework of the CORDEX project.[116] The CORDEX ensemble shows a probable increase of mean annual wind energy output over Northern and Central Europe, and a likely decrease over Southern Europe. The results show uncertainties with respect to the sign and magnitude of the changes, being more robust for specific seasons. In general, changes in projected wind energy output are stronger during the second half of the 21st century and under the RCP8.5 scenario.

Future offshore wind speed and power potential were assessed over the Mediterranean and Black Seas through six RCM simulations carried out by means of three RCMs (RCA3, HIRHAM5, and RACMO) driven by three GCMs (BCM, ECHAM5, and HadCM3) under the A1B and A2 scenarios for two future time periods, 2021–2050 and 2061–2090 within the framework of the ENSEMBLES project.[117] The results show a decrease in both mean wind speed and wind potential over the central Mediterranean Sea, except for an increase over the Aegean and Alboran Seas and the Gulf of Lyon that also presents strong seasonality. Finally, it can be concluded that to know more about the uncertainties related to boundary conditions and intermodel differences, it would be necessary to use a larger ensemble containing more forcing global models, emission scenarios, and ensemble members to sample the natural variability, all having high spatial resolution like those included in the CORDEX project.

More recently, the climate change impact on the future European large-scale wind energy resources was analyzed by means of 21 GCMs from the CMIP5 project under the RCP4.5 and RCP8.5 scenarios for three future time periods, 2015–2016, 2046–2065, and 2081–2100.[118] The multimodel ensemble projects an increase in wind speed in Northern and Central Europe (Baltic Sea and surrounding areas), and a decrease in the Mediterranean area; mainly by the end of the 21st century and under stronger radiative forcing. In addition, although no significant change in the interannual variability of wind speed is projected over Europe, an increase in the intraannual variability of wind is predicted in the Baltic Sea region, and a decrease in the Mediterranean areas. Finally, the authors also concluded that this work serves as a background for future downscaling of CMIP5 data to regional and local scales to focus on climate change impact on wind resources.

The climate change impact on European wind resources was also assessed with a single-model ensemble using the RCA4 RCM driven by five GCMs from the CMIP5 project within the framework of the CORDEX project.[119] Future projections were carried out under the RCP4.5 and RCP8.5 scenarios for two time periods, 2021–2050 and 2061–2090. An overall decrease in wind resources was detected over the European domain, although some regions saw projected increases, such as the Baltic Sea, the Barents Sea, and the Aegean Sea. The change in wind patterns is robust under both scenarios and persists over the 21st century.

More locally, the question about future offshore wind resources in the western Iberian Peninsula under a globally warming climate has been addressed.[120] Future wind projections were carried out by means of six RCMs driven by 14 GCMs under the RCP4.5 and RCP8.5 scenarios within the framework of the CORDEX project from 2071 to 2100. Most of the climate models projected reductions in wind speed and wind power for all seasons except summer. The wind power density increase obtained in the Iberian northwest coast in summer (20%) was able to offset the yearly balance in such a way that no change was expected at a year scale in this area. A yearly reduction of less than 5% in wind power was estimated for the rest of the western Iberian coast. In the particular case of the Canary Islands, future projections of mean wind, wind energy density, and extractable wind power were obtained through WRF dynamical downscaling of the results obtained from an ensemble of 14 GCMs from the CMIP5 project.[121] Future projections were carried out under the RCP4.5 and RCP8.5 scenarios for two future decades, 2045–2054 and 2090–2099. The results show a significant decrease in mean wind speed and extractable wind power offshore during summer, with the exception of some areas near coastlines where a significant increase was obtained, probably due to wind–topography interaction.

Table 5 summarizes all the studies described above, indicating the topic and the area under study and the ensembles used to carry out the analysis. In addition, Figure 4 presents, in conceptual form, the results obtained from these studies under the less favorable GHG scenario for the 21st century. Red (blue) points mark the regions where a wind energy increase (decrease) is projected, and white points mark the regions where no changes are expected.

Effects of the main international, European, and national legal frameworks on the development of offshore wind farms in Europe

Conflicts with other uses, biodiversity conservation, and protection of the marine environment

Offshore wind farms may conflict with other interests that converge in the marine environment (such as navigation, fishing, sand and gravel extraction, military uses, tourism, the laying of submarine cables and pipelines, and biodiversity conservation) throughout their entire life cycle from their installation to their decommissioning.[122] Therefore, it is necessary to analyze the legal responses provided by the international, European, and national legal frameworks. The main regulations are shown in Tables 6 and 7.

At an international level, according to the United Nations Convention on the Law of the Sea of 1982 (UNCLOS), coastal states have full sovereignty over their internal waters and their territorial seas up to 12 nautical miles from the coast. Hence, they have the power to install offshore wind farms, if these respect the right of innocent, continuous, and

Table 5. **Overview of offshore wind and power projections in Europe for the 21st century**

Topic	Place	Models/ensemble
Climate impact on wind energy resources	Europe	ACHAM4/OPYC3 and HadAM3H with RCAO under A2, B2[100]
	Europe	PRUDENCE project, ECHAM4/OPYC3, and HadAM3H with RCAO under A2 and B2[101]
	Mediterranean	HadCM3 with PRECIS under A2 and B2[103]
	Europe	Ensemble of 16 regional simulations with 1RCM, 7GCMs under A1B, A2, and B2[105]
	Ireland	ECHAM4/ECHAM5 with RCA3 under A1B, A2, B1, and B2[109]
	Europe	ECHAM5/MPI-OMR with COSMO CLM (CCLM) and REMO under A1B[110]
	Europe	ENSEMBLES project, 6 GCMs and 10 RCMs under A1B[113]
	Europe	CMIP5 project, ensemble of 21 GCMs[118]
	UK	CMIP3 project, ECHAM5 and HadCM3 under A1B, A2, and B1[108]
	Western Iberian	CORDEX project, ensemble of 14 GCMs with 6 RCMs under RCP4.5 and RCP8.5[120]
	Europe	CORDEX project, ensemble of 5 GCMs with the RCA4 RCM under RCP4.5 and RCP8.5[119]
Extremes wind speed and their future changes	Europe	PRUDENCE project, HadAM3H with 8 RCMs under A2[102]
	Europe	Ensemble of 7 GCMs with 14 RCMs under A1B[104]
	Europe	ECHAM5 with HIRHAM and RCA3 under A1B[107]
	Europe	ENSEMBLE project, 2 GCMs with 4 RCMs under A1B[111]
Present and future offshore wind speed and power potential	Europe	Ensemble of 4 GCMs under A1B[106]
	Europe	CMIP5 project, ECHAM5/MPI-OM under A1B, A2, and B1[115]
	Europe	CORDEX project, 22 GCMs with COSMO-CLM under RCP4.5 and RCP8.5[116]
	Mediterranean and Black Sea	ENSEMBLES project, 3 GCMs with 4 RCMs under A1B and A2[117]
	Baltic Sea	ENSEMBLES project, HadCM3 with CLM_SCN_HadCM3Q under A1B[47]
Wind climate change	North Sea	Ensemble of 8 EC-Earth runs with RACMO2 under RCP8.5[114]
Wind and wind energy production estimations	Ireland	ECHAM5 with COSMO-CLM under A1B and B1[109]
	Canary Islands	CMIP5 project, ensemble of 14 GCMs under RCP4.5 and RCP8.5[121]

uninterrupted passage of foreign ships in the territorial sea (Article 17). In order to ensure safety in navigation, coastal states may designate sea-lanes and traffic separation schemes in the territorial sea as well as require foreign ships, which exercise the right of innocent passage, to use them (Article 22). In this sense, the International Maritime Organization (IMO) has adopted key provisions, such as the Revised Chapter V of the annex to the International Convention for the Safety of Life at Sea of 1974 and the IMO Resolution A.572(14) of 1985, as amended. Two of several examples of the application of both Article 22 of the UNCLOS and IMO´s provisions are:

- The amendments to the traffic separation scheme "Off lands End, Between Longships and Seven Stones"—which were proposed by

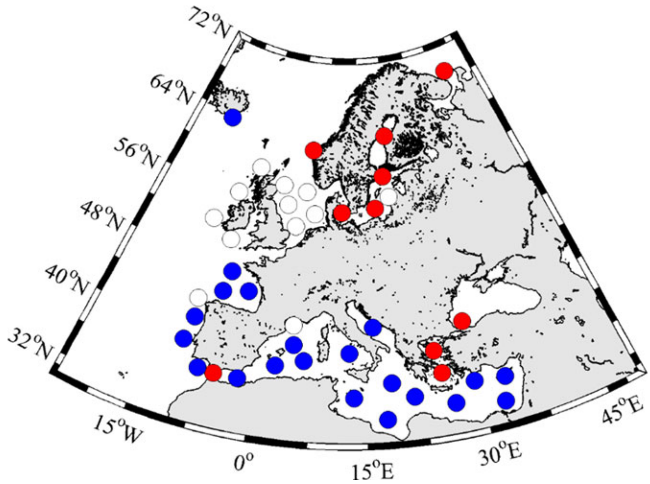

Figure 4. Conceptual map showing the main results obtained from studies of future ocean wind energy resources under the less favorable greenhouse gas scenario for the 21st century. Red (blue) points mark the regions where a wind energy increase (decrease) is projected and white points mark the regions where no changes are expected.

UK to the IMO in 2008 and entered into force in 2009—due to the installation of marine renewable energies.

- The proposal of the Netherlands to the IMO of several measures in 2012 on traffic separation—with the aim of improving the safety of navigation—taking into account renewable energy projects and oil and gas platforms.[123]

In addition, coastal states have sovereignty rights to exploit and manage offshore wind farms (as well as other living or nonliving resources) in their exclusive economic zones (EEZs) from 12 to 200 nautical miles offshore. However, as highlighted by many authors, these facilities must respect freedoms of navigation, overflight, and laying of submarine cables and pipelines that all other states enjoy in the EEZ (Article 56), while not interfering with "the

Table 6. Overview of the main international and European regulations that affect directly the implementation of offshore wind farms

	International law	European law
Marine and biodiversity protection	UNCLOS (Part XII); Regional Seas Conventions (OSPAR, Barcelona, Helsinki and Baltic Conventions); the Convention on Biological Diversity; the Ramsar Convention of Wetlands of International Importance; the Convention on the Conservation of Migratory Species of Wild Animals; the Bern Convention on the Conservation of European Wildlife and Natural Habitats; the Bonn Convention on the Conservation of Migratory Species of Wild Animals; London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	Habitats Directive 92/43/EEC; Birds Directive 2009/147/EC; Marine strategy framework Directive 2008/56/CE; Strategic Environmental Assessment Directive 2001/42/EC; Environmental Impact Assessment Directive 2014/52/EU
Conflicts with other users management	UNCLOS	Marine Spatial Planning Directive 2014/89/EU
Support of renewable energies		Directive 2009/28/EC on the promotion of the use of energy from renewable sources

Table 7. Overview of the main domestic law in offshore wind power in leading European countries

	UK	Germany	The Netherlands	Denmark
Licensing process	The Planning Act (2008); the Marine and Coastal Access Act (2009); the Electricity Act (1989); the Energy Act (2004); the Marine (Scotland) Act (2010)	Offshore Wind Act (WindSeeG) (2017)	Offshore Wind Energy Act (Wet Wind op Zee) (2015)	Promotion of Renewable Energy Act (VE-Lov) (2009)
Support mechanisms	The Energy Act (2013)—the Electricity Market reform (2014)	Renewable Energy Sources Act (EEG) (2017); Offshore wind Act (WindSeeG) (2017)	SDE + Decree (Besluit stimulering duurzame energieproductie) (2007)	Promotion of Renewable Energy Act (VE-Lov) (2009)

UNCLOS, United Nations Convention on the Law of the Sea; OSPAR, Convention for the Protection of the Marine Environment of the North East Atlantic.

use of recognized lanes essential to international navigation" (Article 60.7).[123–125] Coastal states have the obligation to ensure the removal of abandoned or disused facilities located in their EEZ, with due regard to "fishing, the marine environment protection, and the rights and duties of the other states" (Article 60.3). The last sentence of this provision leaves the door open to exceptions to the general rule of total removal.[123] In this regard, several studies have shown that offshore wind turbine foundations can act as artificial reefs around which a new habitat develops, concluding that partial removal (conserving mainly the base and cable covers) could be more beneficial for preservation of these new habitats than total removal of the facilities.[126] In regards to the continental shelf, its legal regime has special importance in relation to the transportation of the energy produced by the offshore wind farms.[127] On the one hand, any (coastal or noncoastal) state has the right of laying submarine cables and pipelines on the continental shelf, provided that they meet the requirements set in Article 79, which are mainly: the need to obtain the consent of the coastal state with regard to the delineation of the course for the laying of pipelines on the continental shelf and the need to take into account those submarine cables and pipelines already in position. On the other hand, the coastal state has jurisdiction over cables and pipelines laid on its continental shelf, as well as the right to establish the conditions for cables or pipelines entering in its territory or territorial sea, and to regulate and authorize drilling on its continental shelf (e.g., for installing offshore wind foundations) (Articles 79 and 81).[127] In addition, any (coastal or noncoastal) state has the power to install offshore wind farms on the high seas based on the general principle of freedom that governs beyond 200 nautical miles under UNCLOS. However, nowadays, according to the status of the technology, the development of offshore wind farms on the high seas is infeasible due to technical difficulties derived from the distance from the coast and the water depth.

On the EU level, Maritime Spatial Planning Directive 2014/89/EU (MSPD), whose objectives include "the sustainable development of energy sectors at sea" (Article 5.2), may help prevent and avoid conflicts between offshore wind farms and other interests that converge in the marine environment, offering greater certainty and security to investors in marine renewable energy and helping to reduce the processing times required for installation of these facilities.[128,129] In this sense, MSPD requires member states to draw up their respective maritime spatial plans before March 31, 2021 (Article 15.3), specifying present and future spatio-temporal distribution of their various relevant activities in their marine waters, such as "installations and infrastructures [. . .] of the production of renewable sources [. . .] or submarine cable and pipeline routes," taking into consideration their main interactions (Articles 8.1 and 8.2). Member states have a considerable degree of leeway to set, prioritize, and distribute each concrete use of their offshore waters, and there are notable differences among their respective multisectoral partnerships. For instance, Germany and the Netherlands do not provide for the establishment of offshore wind farms in marine protected areas (such as the Natura 2000 sites) or in the areas visible from the coast (due to landscape impact reasons), whereas UK opens the door to the possibility of coexistence between offshore wind farms and Natura 2000 network sites in certain cases and does not exclude construction of these devices in areas visible from the coast.[130,131]

Moreover, Marine Strategy Framework Directive 2008/56/EC (MSFD) can be very helpful in avoiding conflicts between protection of biodiversity and the marine environment, and development of offshore wind farms.[122] This directive is aimed at achieving and maintaining a good environmental status (GES) of the marine environment by 2020, by eliminating pollution and protecting the marine environment through development and implementation of marine strategies (Articles 1 and 3 MSFD). Annex I of MSFD establishes a list of 11 descriptors of a GES, such as the maintenance of biodiversity, the integrity of the sea floor, and the level of introduced energy (included underwater noise). These indicators are related to many impacts caused by offshore wind farms, including collision of birds and bats with turbines, changes to and destruction of habitats (marine biodiversity loss or reduction) due to acoustic disturbance and electromagnetic fields produced from submarine cables, and hazards to shipping or threats to maritime safety.[122]

Furthermore, the Marine Regional Conventions (the OSPAR, Barcelona, Helsinki and Baltic Conventions) can help address possible environmental concerns derived from installation of offshore wind farms, improving regional coordination and cooperation among states within the same marine basin in developing their "marine strategies" and their "maritime spatial plans."[122]

Likewise, the Habitat Directive (92/43/EEC) and the Birds Directive (2009/147/EC) set out a general protection system for conservation of all wild bird species present in the EU (Article 5, Birds Directive), and other species and habitat types (Articles 12 and 13, Habitats Directive).[124,132] These directives also establish a specific protection scheme by designating protected areas that are part of the Natura 2000 network created by the Habitats Directive. Under this protection system, member states initially designate the Special Areas of Conservation that subsequently are proposed to the European Commission (EC) for approval as the Sites of Community Importance. Likewise, Special Protection Areas are also designated for the specific protection of wild and migratory birds.[132] In the event that the installation and operation of offshore wind farms is likely to have a negative impact on a site within the Natura 2000 network, the plan or project must be subject to a "proper assessment" of its effects on the site (Article 6.3, Habitats Directive) to decide whether the proposed facilities are suitable. However, even if the result of the assessment is negative, these directives leave the door open to develop offshore wind farms if the necessary specific mitigation measures or alternative measures that may be required by the national authorities are taken, or even in the absence of alternative solutions, if there are "overriding reasons of public interest of the highest order, including social or economic reasons" and if necessary compensatory measures are implemented (Article 6.4, Habitats Directive).[124,132]

In addition, other EU directives are aimed at preventing the development of adverse effects on the marine environment and ensuring the protection of biodiversity arising from the installation of offshore wind farms, such as Directive 2001/42/EC on assessment of the effects of certain plans and programs on the environment, which subjects public plans and programs to a strategic environmental assessment of their probable effects on the environment, and Directive 2014/52/EU amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, which subjects concrete private or public projects to an environmental impact assessment.

Licensing process

The licensing process has been pointed out by the EC and the scientific literature as one of the major obstacles to development of marine renewable energies.[133,134] In particular, lengthy and complex procedures with a large number of authorities involved have been identified as major bureaucratic barriers.[135,136] Scientific doctrine and the EC have highlighted the need to streamline these licensing procedures by improving coordination among various agencies involved and reducing the number of consent bodies and authorizations required.[137] Many of these measures have been implemented by leading European countries in offshore wind farm development.[138] In this sense, Denmark and

Scotland have adopted a One-Stop-Shop system, in which a single authority (the Danish Energy Agency in Denmark and Marine Scotland's Licensing Operations Team in Scotland) processes the main authorizations required to install and operate an offshore wind farm.[139,140] Likewise, England has reduced the number of consent bodies and licenses required to install offshore wind farms, resulting in a significant simplification and reduction of the processing time needed to obtain relevant authorizations.[135,141] Table 8 lists the main licenses required in leading European countries (England, Scotland, Germany, the Netherlands, and Denmark), as well as the consent bodies responsible for granting each.

On the other hand, scientific uncertainty about environmental effects caused by these sea-based facilities has also been reported as a cause of delays due to repeated requests for data and environmental information by agencies to promoters, who may be required to carry out massive research operations before construction of small facilities that pose a low risk to the marine environment.[135,136,142] To solve this problem, several authors and the Ocean Energy Forum have proposed the adoption of a risk-based approach and the implementation of regulations that establish administrative requirements proportional to the risk and magnitude of the installation.[134,142,143] Likewise, an active role for government in carrying out preliminary research work, as established in the Netherlands, could relieve the burden on promoters of collecting unnecessary and repetitive data and could thus encourage the development of marine renewable technologies.[144]

Support schemes, political will, and grid connection

Political will and various mechanisms for promoting renewable energy sources are important variables with a strong influence on the development of offshore wind farms.[145]

Three main support schemes developed in Europe to promote the implementation of renewable energies are shown in Table 8. The feed-in-tariff system in which renewable energy producers receive a fixed remuneration per MWh was generated that does not depend on the price in the electricity market, meaning that producers take on little risk.[141,146] Germany has traditionally followed this system of fixed prices. However, a market premium system has been adopted since 2012.

The feed-in-premium system was adopted by the Netherlands, Denmark, and Germany since 2012, in which a payment (fixed or flexible) is added to the price in the electricity market.[146] This system is sensitive to market fluctuations and poses a certain risk for producers. However, it also enables generators to enjoy high benefits in case market electricity prices rise.

The quota system is traditionally followed by UK in which suppliers are obliged to supply the final consumer with a certain amount of energy from renewable sources. To help them fulfill this obligation, the authority issues tradable green certificates (renewable obligation certificates (ROCs) in the case of UK) that are sold in the open market by generators to suppliers. If suppliers do not gather enough ROCs to fulfill their obligation, they will be sanctioned financially.[141,146] However, ROCs have been replaced by a contracts-for-difference system since 2017 in UK. Under this new model, a government-owned counterpart (a low-carbon contracting company) guarantees the generator a payment for a certain number of years consisting of the difference between the price agreed upon in the contract (the strike price) and the market price.[138]

Other widely used measures to promote marine renewable energy consist of tax exemptions (e.g., the climate change levy exemption in UK), free connections to the grid (as used by Germany in the EEZ under certain circumstances, such as a rapid commissioning sprinter bonus), capital grants, financial support incentives for research, technological development, and testing and development of experimental projects (such as the creation of specific support agencies (funding bodies in UK, e.g., the Department of Energy and Climate Change)).[137,141,145]

The 2009/28/EC Directive on promoting use of energy from renewable sources sets a target of at least 20% share of energy from renewable sources in the EU's gross final energy consumption in 2020. To achieve this goal, the 2009/28/EC Directive establishes a general framework to promote renewable energies and proposes transnational cooperation mechanisms (e.g., statistical data transfer, joint support schemes, and joint projects).[128,146]

The 2014/C 200/01 Communication from the EC indicates that subsidies to renewable energy producers must be progressively reduced in favor of

Table 8. Overview of main licenses for offshore wind development required in leading European countries, as well as the consent bodies responsible for granting each

Countries		Main licenses required	Main consent bodies	Tender (centralized/ decentralized)/open door	Main support schemes (support period)
UK[a]	England (projects of +100 MW of installed capacity)	(1) Development consent	(1) The Secretary of State, previous recommendations of the Planning Inspectorate (which processes the main steps of the licensing procedure)	Tender (decentralized)	Contracts for Difference (15 years); Climate change levy exemption
	England (–100 MW)	(1) Section 36 Consent (electricity act 1989) (2) Marine License (3) Onshore works consent	1), 2) The Marine Management Organization (which processes the main steps of the licensing procedure)3) The relevant planning authority		
	Scotland	(1) Section 36 Consent (2) Marine License Consent (3) Onshore works consent	1), 2), 3) Marine Scotland Licensing Operations Team (which processes the main steps of the licensing procedure)		
Germany[b]		(1) Planning approval (to install offshore wind farms in the EEZ) (2) Cabling approval (to lay cables in the territorial sea)	(1) The Federal Maritime and Hydrographic Agency (BSH) (which carries out preliminary investigations and processes the main steps of the licensing procedure) (2) The authorities of the relevant German coastal state	Tender (centralized)	Sliding Feed-in premium (20 years); The KfW-Program offshore wind energy, which offers low interest loans and financing packages for investments in offshore wind farms
The Netherlands		(1) The wind license (single consent that combines land tenure and permission to build)	(1) The Netherlands Enterprise Agency (RVO.nl) (which carries out preliminary investigations and processes the main steps of the licensing procedure)-on behalf of the Ministry of Economic Affairs and Climate Policy	Tender (centralized)	SDE+: a subsidy, which consists of the difference between the tender amount—considering costs and a reasonable profit— and the correction amount—the market power price— (15 years after subsidy grant); tax credits aimed at promoting investments in renewable energies

(continued)

Table 8. Continued

Countries	Main licenses required	Main consent bodies	Tender (centralized/ decentralized)/open door	Main support schemes (support period)
Denmark	(1) License to carry out preliminary works (2) License to install offshore wind farms (3) License to exploit offshore wind farms	The Danish Energy Agency (which carries out preliminary investigations and processes the main steps of the licensing procedure)	Tender (centralized)/ open door	Sliding Feed-in premium (50,000 full load hours or 20 years); loan guarantees for local initiatives for the construction of offshore wind farms

EEZ, exclusive economic zone; BSH, The Bundesamt für Seeschifffahrt und Hydrographie; KfW, it is a German government-owned development bank; RVO.nl, Rijksdienst voor Ondernemend Nederland; SDE+, stimulering Duurzame Energieproductie (stimulation of sustainable energy production).

[a]The promoters selected in the tendering procedure have to subscribe an agreement of lease with the Crown Estate (as owner of the seabed) before obtaining the required licenses, and then, provided that these licenses are obtained, the Crown State will grant the lease. The licensing process is slightly different in each region of UK as shown in the table. Apart from the licenses shown in the table, promoters have to obtain Safety Zones Consent and decommissioning approval, which are issued by the Department of Energy and Climate Change in both England and Scotland.

[b]The BSH is the agency responsible for issuing planning approval for those projects which aim to be located in German exclusive economic zone. However, if the projects aim to be located within the territorial sea, permits necessary to install them are granted by authorities of the relevant German Coastal State.

market-based instruments such as auctions or tendering procedures (point 108). Point 126 establishes that aid for renewable energy producers must generally be granted through "clear, transparent, and nondiscriminatory" tendering procedures from January 1, 2017 onward. In this sense, both the Netherlands (after the reform of 2015) and Germany (after approval of the offshore wind act of 2017 (the WindSeeG)) have moved away from their traditional first-come-first-served system, which was open to the risk of reducing competition between promoters and encouraging speculation, to the tendering procedure adopted by Denmark and UK.[137] The auction system includes two models of site organization and selection: (1) a centralized model (adopted by Denmark, the Netherlands, and Germany), in which the government determines before the tendering procedure the specific sites where offshore wind farms are to be located and carries out predevelopment work, and (2) a decentralized model (adopted by UK), in which specific sites for wind farm installations within offered zones are proposed by several developers (Table 8).[147] According to WindEurope, the advantages associated with a centralized approach are simpler licensing procedures and reduced transaction costs for developers, whereas the advantages associated with a decentralized approach are greater competition between developers and less socialization of costs. Implementation of prechecks (e.g., the obligation to present financial guarantees) and penalties (in the case of noncompliance with the procedures) on the bidders can help ensure completion of the offshore wind farm by the selected developer. However, overly strict requirements can reduce significantly the participation of bidders and the competition between them.[147]

With regard to the connection of offshore wind farms to the network, the offshore transmission system operator (TSO) model, under which the TSOs are obliged to provide grid connections, but the owner of each offshore wind farm is responsible for connecting it to the offshore transmission system, appears to be the most widespread mechanism implemented in Europe (e.g., in Denmark, Germany, and the Netherlands).[138] However, other countries, such as UK, follow a third party model, in which a third party—the offshore transmission owner, selected after a competitive tender—is responsible for connecting the offshore wind farm to the onshore system.[138] The costs of constructing and operating the connection to the onshore network can be recovered by charging these costs directly to the owner of the connected offshore wind farm (as in UK) or through a TSO levy payable by all users (as in Denmark and Germany).[138]

Concluding remarks

During the last decade, renewable energy development has been shown to be crucial in the fight against climate change because it has proved to provide clean and sustainable sources of energy and to offer an alternative to fossil fuel combustion, which is the largest contributor to ocean and atmospheric warming. Wind energy is one of the leaders in terms of installed power capacity, fast growth, and technological maturity and remains the second largest form of power generation capacity in the EU, closely approaching gas installations. Offshore wind farms have considerable advantages over onshore ones, such as generally higher wind speeds with lower turbulence and variability, availability of larger areas for wind farms, and lower visual impact from the coast.

Under this scenario, almost all present or potential European locations for offshore windfarms were studied and analyzed from the point of view of their use as a wind energy resource (Fig. 3). However, the future offshore wind and wind power projections for the 21st century under the most unfavorable GHG scenario show that only Northern Europe and some particular locations such as the northwestern part of the Iberian Peninsula, the Gulf of Lyon, the Strait of Gibraltar, and the northwest coast of Turkey will experience no change or increase in wind and power energy (Fig. 4). Therefore, these locations appear to be the most suitable for installing or maintaining offshore wind farms. Most of these locations coincide with the locations of active wind farms (Fig. 1B) or wind farms that are under construction, approved, or planned for the near future (Fig. 1B). These kinds of studies can help policymakers to make policies and laws to facilitate offshore wind farm development at these locations.

Installation of offshore wind farms is subject to several restrictions established under international law (e.g., respecting international sea-lanes widely recognized by nations), European law (e.g., the conservation of Natura 2000 sites), and the domestic legal framework of each member state. In addition, other legal-political variables, such as the duration and degree of complexity of licensing processes and the financial aid systems established by each member state, may influence promoters' decisions when they select the best sites for locating offshore wind farms in Europe. At present, the general trend in Europe points toward streamlining of licensing procedures, reducing subsidies, and implementing auction systems.

Acknowledgments

This research was partially supported by Xunta de Galicia under Project ED431C 2017/64 "Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas (Grupos de Referencia Competitiva)" cofunded by European Regional Development Fund (FEDER) and under Project "NUMANTIA ED431F 2016/004." X.C. is supported by the Portuguese Science Foundation (FCT) through a postdoctoral grant (SFRH/BPD/118142/2016). S.S. is supported by the Xunta of Galicia through a predoctoral grant (ED481A-2016/36).

Competing interests

The authors declare no competing interests.

References

1. Intergovernmental Panel on Climate Change (IPCC). 2014. Fifth assessment report 2014. Accessed July 3, 2018. http://www.ipcc.ch/report/ar5/.
2. REN21. 2017. Renewables 2017 global status report. REN21 Secretariat, Paris. ISBN 978-3-9818107-6-9. Accessed July 3, 2018. http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf.
3. Wind in Power 2017. 2018. Annual combined onshore and offshore wind energy statistics. Wind Europe executive summary. Accessed July 3, 2018. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2017.pdf.
4. Chadee, X.T. & R.M. Clarke. 2018. Wind resources and the levelized cost of wind generated electricity in the Caribbean islands of Trinidad and Tobago. *Renew. Sustain. Energy Rev.* **81:** 2526–2540.
5. Offshore Wind in Europe. 2018. Key trends and statistics 2017. Wind Europe executive summary. Accessed July 3, 2018. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2017.pdf.
6. Ragheb, M. & A.M. Ragheb. 2011. Wind turbines theory—the Betz equation and optimal rotor tip speed ratio. In *Fundamental and Advanced Topics in Wind Power*. R. Carriveau, Ed. InTech. https://doi.org/10.5772/21398
7. Jones, B. 1950. *Elements of Aerodynamics*. New York, NY: John Wiley & Sons. pp. 73–158.
8. Betz, A. 1926. Windenergie und ihre ausnutzung durch wind-muhlen: Vandenhoeckund ruprecht.
9. Hennessey, J.P. 1977. Some aspects of wind power statistics. *J. Appl. Meteorol.* **16:** 119–128.
10. Monahan, A.H. 2006. The probability distribution of sea surface wind speeds. Part I: theory and sea winds observations. *J. Clim.* **19:** 497–520.

11. Morgan, E. C., M. Lackner, R.M. Vogel, *et al.* 2011. Probability distributions for offshore wind speeds. *Energy Convers. Manage.* **52:** 15–26.
12. Stevens, M.J. & P.T. Smulders. 1979. The estimation of the parameters of the Weibull wind speed distribution for wind energy utilization purposes. *Wind Eng.* **3:** 132e45.
13. Seguro, J.V. & T.W. Lambert. 2000. Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. *J. Wind Eng. Ind. Aerodyn.* **85:** 75e84.
14. Swart, R.J., C. Coppens, H. Gordijn, *et al.* 2009. Europe's onshore and offshore wind energy potential: an assessment of environmental and economic constraints (No. 6/2009). European Environment Agency.
15. Hasager, C.B., D. Stein, M. Courtney, *et al.* 2013. Hub height ocean winds over the North Sea observed by the NORSEWInD lidar array: measuring techniques, quality control and data management. *Remote Sens.* **5:** 4280–4303.
16. Karimirad, M. 2014. Floating offshore wind turbines. In *Offshore Energy Structures for Wind Power, Wave Energy and Hybrid Marine Platforms.* pp. 53–76. Springer.
17. Tennekes, H. 1973. The logarithmic wind profile. *J. Atmos. Sci.* **30:** 234–238.
18. Monin, A.S. & A.M. Obukhov. 1954. Osnovnye zakonomernosti turbulentnogo peremeshivanija v prizemnom sloe atmosfery (Basic laws of turbulent mixing in the atmosphere near the ground). *Trudy Geofiz Inst. AN. SSSR.* **24:** 163–187.
19. Peixoto, J.P. & A.H. Oort. 1992. *Physics of Climate.* Woodbury, NY: American Institute of Physics.
20. Carvalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2014. Offshore wind energy resource simulation forced by different reanalyses: comparison with observed data in the Iberian Peninsula. *Appl. Energy* **134:** 57–64.
21. Paulson, C.A. 1970. The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. *J. Appl. Meteorol.* **9:** 857e61.
22. Sempreviva, A.M., R.J. Barthelmie & S.C. Pryor. 2008. Review of methodologies for offshore wind resource assessment in European seas. *Surv. Geophys.* **29:** 471–497.
23. Rodrigo, J.S., E. Cantero, B. García, *et al.* 2015. Atmospheric stability assessment for the characterization of offshore wind conditions. *J. Phys. Conf. Ser.* **625:** 012044.
24. Hoogwijk, M., B. de Vries & W. Turkenburg. 2004. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. *Energy Econ.* **26:** 889–919.
25. Yamada, T. & G. Mellor. 1975. A simulation of the Wangara atmospheric boundary layer data. *J. Atmos. Sci.* **32:** 2309–2329.
26. Atlas, R., R.N. Hoffman, J. Ardizzone, *et al.* 2011. A cross-calibrated, multiplatform ocean surface wind velocity product for meteorological and oceanographic applications. *Bull. Am. Meteorol. Soc.* **92:** 157–174.
27. Wentz, F.J., L. Ricciardulli, E. Rodriguez, *et al.* 2017. Evaluating and extending the ocean wind climate data record. *IEEE J-STARS* **10:** 2165–2185.
28. Kent, E.C., S. Fangohr & D.I. Berry. 2013. A comparative assessment of monthly mean wind speed products over the global ocean. *Int. J. Climatol.* **33:** 2520–2541.
29. Portabella, M. & A. Stoffelen. 2001. Rain detection and quality control of SeaWinds. *J. Atmos. Ocean Tech. Technol.* **18:** 1171–1183.
30. Furevik, B.R., A.M. Sempreviva, L. Cavaleri, *et al.* 2010. Eight years of wind measurements from scatterometer for wind resource mapping in the Mediterranean Sea. *Wind Energy* **14:** 355–372.
31. Hasager, C.B. 2014. Offshore winds mapped from satellite remote sensing. *WIRES Energy Environ.* **3:** 594–603.
32. Christiansen, M., B. Koch, W. Horstmann, *et al.* 2006. Wind resource assessment from C-band SAR. *Remote Sens. Environ.* **105:** 68–81.
33. Young, I.R., S. Zieger & A.V. Babanin. 2011. Global trends in wind speed and wave height. *Science* **332:** 451–455.
34. Mikkelsen, T., S. Siggaard Knudsen, M. Sjöholm, *et al.* 2012. WindScanner.eu—a new remote sensing research infrastructure for on- and offshore wind energy. In *Proceedings of the International Conference on Wind Energy: Materials, Engineering and Policies.*
35. Hasager, C.B., A. Peña, M.B. Christiansen, *et al.* 2008. Remote sensing observation used in offshore wind energy. *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.* **1:** 67–79.
36. Hansen, K., M. Courtney, P. Hummelshøj, *et al.* 2007. Validation of SODAR measurements for wind power assessment. In *Proceedings of the European Wind Energy Conference*, Athens.
37. Pichugina, Y.L., R.M. Banta, W.A. Brewer, *et al.* 2012. Doppler lidar–based wind-profile measurement system for offshore wind-energy and other marine boundary layer applications. *J. Appl. Meteorol. Clim.* **51:** 327–349.
38. Peña, A., C.B. Hasager, J. Lange, *et al.* 2013. Remote sensing for wind energy. DTU Wind Energy. Report No. 0029(EN). Accessed July 3, 2018. http://orbit.dtu.dk/.
39. Smith, M. 2012. An insight into lidars for offshore wind measurements. In *Deepwind 2012 Conference*, Trondheim.
40. Gottschall, J., B. Gribben, D. Stein & I. Würth. 2017. Floating lidar as an advanced offshore wind speed measurement technique: current technology status and gap analysis in regard to full maturity. *WIRES Energy Environ.* **6:** e250.
41. Christiansen, M.B. & C.B. Hasager. 2006. Using airborne and satellite SAR for wake mapping offshore. *Wind Energy* **9:** 437–455.
42. Trenberth, K.E., R. Dole, Y. Xue, *et al.* 2010. Atmospheric reanalyses: a major resource for ocean product development and modeling. In *Proceedings of "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference.* Vol. 2. J. Hall, D. E. Harrison & D. Stammer, Eds. ESA Publication WPP-306, Venice.
43. Carvalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2014. Comparison of reanalyzed, analyzed, satellite-retrieved and NWP modelled winds with buoy data along the Iberian Peninsula coast. *Remote Sens. Environ.* **152:** 480e92.
44. Fitch, A.C., J.B. Olson, J.K. Lundquist, *et al.* 2012. Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. *Mon. Weather Rev.* **140:** 3017–3038.
45. Fang, H.F. 2014. Wind energy potential assessment for the offshore areas of Taiwan west coast and Penghu Archipelago. *Renew. Energy* **67:** 237–241.

46. Soukissian, T. H. & A. Papadopoulos. 2015. Effects of different wind data sources in offshore wind power assessment. *Renew. Energy* **77:** 101–114.
47. Lizuma, L., Z. Avotniece, S. Rupainis & A. Teilans. 2013. Assessment of the present and future offshore wind power potential: a case study in a target territory of the Baltic Sea near the Latvian Coast. *Sci. World J.* **2013:** 10.
48. Hoffman, R.N. & S.M. Leidner. 2005. An introduction to the near–real-time QuikSCAT data. *Weather Forecast.* **20:** 476–493.
49. Verhoef, A. & A. Stoffelen. 2016. ASCAT L2 winds data record product user manual version 1.2. Document external project: SAF/OSI/CDOP2/KNMI/TEC/MA/238. EUMETSAT.
50. Verspeek, J., A. Verhoef & A. Stoffelen. 2013. ASCAT-B NWP ocean calibration and validation. Document external project: SAF/OSI/CDOP2/KNMI/TEC/RP/199. EUMETSAT.
51. Verhoef, A. & A. Stoffelen. 2012. OSCAT winds validation report version 1.0. Document external project: SAF/OSI/CDOP2/KNMI/TEC/RP/196. EUMETSAT.
52. OSI SAF. 2015. RapidScat wind product user manual. KNMI, De Bilt. SAF/OSI/CDOP2/KNMI/TEC/MA/227.
53. Bao, L., P. Gao, H. Peng, *et al.* 2015. First accuracy assessment of the HY-2A altimeter sea surface height observations: cross-calibration results. *Adv. Space Res.* **55:** 90–105.
54. Duchossois, G. & P. Martin. 1995. ERS-1 and ERS-2 tandem operations. *ESA Bull.* No. 83, pp. 54–60.
55. Foti, G., C. Finch, J. Vazquez, *et al.* 2013. Aquarius user guide, Aquarius Dataset Version 2.0. Aquarius Project Document AQ-010-UG-0008. California Institute of Technology, Pasadena, CA.
56. Gaiser, P.W., K.M. St Germain, E.M. Twarog, *et al.* 2004. The WindSat spaceborne polarimetric microwave radiometer: sensor description and early orbit performance. *IEEE Trans. Geosci. Remote Sens.* **42:** 2347–2361.
57. Wentz, F.J., P.D. Ashcroft & C.L. Gentemann. 2001. Post-launch calibration of the TRMM microwave imager. *IEEE Trans. Geosci. Remote* **39:** 415–422.
58. Entekhabi, D., S. Yueh, P.E. O'Neill, *et al.* 2014. *SMAP Handbook—Soil Moisture Active Passive: Mapping Soil Moisture and Freeze/Thaw from Space.* Pasadena, CA: California Institute of Technology.
59. Reul, N., J. Tenerelli, B. Chapron, *et al.* 2012. SMOS satellite L-band radiometer: a new capability for ocean surface remote sensing in hurricanes. *J. Geophys. Res. Oceans* **117**. https://doi.org/10.1029/2011JC007474.
60. Wentz, F.J. & T. Meissner. 2007. Supplement 1 algorithm theoretical basis document for AMSR-E ocean algorithms. NASA, Santa Rosa, CA.
61. JAXA. 2013. Data users' manual for the advanced microwave scanning radiometer 2 (AMSR2) onboard the global change observation mission 1st—water "SHIZUKU" (GCOM-W1). 2nd ed. Accessed July 3, 2018. http://suzaku.eorc.jaxa.jp/GCOM_W/data/doc/amsr2_data_user_guide.pdf.
62. Wentz, F.J. 2013. SSM/I version-7 calibration report. Report number 011012. Remote Sensing Systems, Santa Rosa, CA, 46 pp.
63. Draper, D.W., D. Newell, F.J. Wentz, *et al.* 2015. The global precipitation measurement (GPM) microwave imager (GMI): instrument overview and early on-orbit performance. *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.* **8:** 3452–3462.
64. Kanamitsu, M., W. Ebisuzaki, J. Woollen, *et al.* 2002. NCEP-DOE AMIP-II reanalysis (R-2). *Bull. Am. Meteorol. Soc.* **83**: 1631–1643.
65. Saha, S., S. Moorthi, H.L. Pan, *et al.* 2010. The NCEP climate forecast system reanalysis. *Bull. Am. Meteorol. Soc.* **91:** 1015–1057.
66. Rienecker, M.M., M.J. Suarez, R. Gelaro, *et al.* 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. *J. Clim.* **24:** 3624–3648.
67. Hahmann, A.N., D. Rostkier-Edelstein, T.T. Warner, *et al.* 2010. A reanalysis system for the generation of mesoscale climatographies. *J. Appl. Meteorol. Clim.* **49:** 954–972.
68. Dee, D.P., S.M. Uppala, A.J. Simmons, *et al.* 2011. The ERA—interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteor. Soc.* **137:** 553–597.
69. ECMWF. 2016. IFS documentation CY41R2. ECMWF, Reading.
70. Kobayashi, S. & National Center for Atmospheric Research Staff. 2017. The climate data guide: JRA-55. August 11, 2017. Accessed September 15, 2017. https://climatedataguide.ucar.edu/climate-data/jra-55.
71. NCEP. 2000. NCEP GDAS/FNL 0.25 degree global tropospheric analyses and forecast grids. Research data archive at the Computational and Information Systems Laboratory, National Center for Atmospheric Research. Boulder, CO. Accessed September 18, 2017. https://rda.ucar.edu/datasets/ds083.2/.
72. EMC. 2016. The global forecast system (GFS)—global spectral model (GSM) (GSM version 13.0.2). Final report. Environmental Modeling Center. Accessed September 17, 2017. http://www.emc.ncep.noaa.gov/GFS/doc.php.
73. Zhang, H.-M., J.J. Bates & R.W. Reynolds. 2006. Assessment of composite global sampling: sea surface wind speed. *Geophys. Res. Lett.* **33:** L17714.
74. Wentz, F.J., J. Scott, R. Hoffman, *et al.* 2015. Remote Sensing Systems Cross-Calibrated Multi-Platform (CCMP) 6-hourly ocean vector wind analysis product on 0.25 deg grid, version 2.0. In *Proceedings of Remote Sensing Systems*, Santa Rosa, CA.
75. Yu, L., X. Jin & R.A. Weller. 2008. (Woods Hole Oceanographic Institution). Multidecade global flux datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Woods Hole Oceanographic Institution, Woods Hole, MA. Report No. OA-2008-01.
76. Bentamy, A. & D. Croizé-Fillon. 2011. Gridded surface wind fields from Metop/ASCAT measurements. *Int. J. Remote Sens.* **33:** 1729–1754.

77. Kucukali, S. & Ç. Dinçkal. 2014. Wind energy resource assessment of Izmit in the West Black Sea Coastal Region of Turkey. *Renew. Sustain. Energy Rev.* **30:** 790–795.
78. Akpınar, A. 2013. Evaluation of wind energy potentiality at coastal locations along the north eastern coasts of Turkey. *Energy* **50:** 395–405.
79. Erdoğan, B., S.E. Altınışık, H. Angaç, *et al.* 2012. The modeling of weather conditions and wind power in cities of Western Black Sea Region by using linear regression method. In *IRENEC Conference*, Istanbul. pp. 143–149.
80. Ucar, A. & F. Balo. 2010. Assessment of wind power potential for turbine installation in coastal areas of Turkey. *Renew. Sustain. Energy Rev.* **14:** 901–1912.
81. Sahin, B., M. Bilgili & H. Akıllı. 2005. The wind power potential of the eastern Mediterranean region of Turkey. *J. Wind Eng. Ind. Aerodyn.* **93:** 171–183.
82. Hasager, C.B, M. Badger, A. Peña, *et al.* 2011. SAR-based wind resource statistics in the Baltic. *Sea Remote Sens.* **3:** 117–144.
83. Hasager, C.B., R.J. Barthelmie, M.B. Christiansen, *et al.* 2006. Quantifying offshore wind resources from satellite wind maps: study area the North Sea. *Wind Energy* **9:** 63–74.
84. Johannessen, O.M. & E. Bjorgo. 2010. Wind energy mapping of coastal zones by synthetic aperture radar (SAR) for siting potential windmill locations. *Int. J. Remote Sens.* **21:** 1781–1786.
85. Badger, M., J. Badger, M. Nielsen, *et al.* 2010. Wind class sampling of satellite SAR imagery for offshore wind resource mapping. *J. Appl. Meteorol. Climatol.* **49:** 2474–2491.
86. Raileanu, A.B., F. Onea & E. Rusu. 2015. Evaluation of the offshore wind resources in the European seas based on satellite measurements. In *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, SGEM1(4). pp. 227–234.
87. Soukissian, T., F. Karathanasi & P. Axaopoulos. 2017. Satellite-based offshore wind resource assessment in the Mediterranean Sea. *IEEE J. Oceanic Eng.* **42:** 73–86.
88. Karamanis, D., C. Tsabaris, K. Stamoulis, *et al.* 2011. Wind energy resources in the Ionian Sea. *Renew. Energy* **36:** 815–822.
89. Hasager, C.B., A. Mouche, M. Badger, *et al.* 2015. Offshore wind climatology based on synergetic use of Envisat ASAR, ASCAT and QuikSCAT. *Remote Sens. Environ.* **156:** 247–263.
90. Karagali, I., M. Badger, A.N. Hahmann, *et al.* 2013. Spatial and temporal variability of winds in the Northern European Seas. *Renew. Energy* **57:** 200–210.
91. Ban, M., L. Perković, N. Duić, *et al.* 2013. Estimating the spatial distribution of high altitude wind energy potential in Southeast Europe. *Energy* **57:** 24–29.
92. Kalogeri, C., G. Galanis, C. Spyrou, *et al.* 2017. Assessing the European offshore wind and wave energy resource for combined exploitation. *Renew. Energy* **101:** 244–264.
93. Onea, F., L. Deleanu, L. Rusu, *et al.* 2016. Evaluation of the wind energy potential along the Mediterranean Sea coasts. *Energy EXPLOR. EXPLOIT.* **34:** 766–792.
94. Alvarez, I., M. Gomez-Gesteira, M. deCastro, *et al.* 2014. Comparison of different wind products and buoy wind data with seasonality and interannual climate variability in the southern Bay of Biscay (2000–2009). *Deep-Sea Res. II* **106:** 38–48.
95. Carvalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2013. Comparison between CCMP, QuikSCAT and buoy winds along the Iberian Peninsula coast. *Remote Sens. Environ.* **137:** 173–183.
96. Carvalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2017. Offshore winds and wind energy production estimates derived from ASCAT, OSCAT, numerical weather prediction models and buoys–a comparative study for the Iberian Peninsula Atlantic coast. *Renew. Energy* **102**(Part B): 433–444.
97. Carvalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2012. Ocean surface wind simulation forced by different reanalyses: comparison with observed data along the Iberian Peninsula coast. *Ocean Model.* **56:** 31–42.
98. Carvalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2014. Sensitivity of the WRF model wind simulation and wind energy production estimates to planetary boundary layer parameterizations for onshore and offshore areas in the Iberian Peninsula. *Appl. Energy* **135:** 234–246.
99. Jimenez, B., F. Durante, B. Lange, *et al.* 2005. Offshore wind resource assessment with WAsP and MM5: comparative study for the German bight. *Wind Energy* **8:** 403–419.
100. Pryor, S.C. & R.J. Barthelmie. 2004. Use of RCM simulations to assess the impact change on wind energy availability. Riso-R1477 (EN). Rep. No. 111.
101. Pryor, S., R. Barthelmie & E. Kjellstrom. 2005. Potential climate change impact on wind energy resources in northern Europe analyses using a regional climate model. *Clim. Dyn.* **25:** 815–835.
102. Rockel, B. & K. Woth. 2007. Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble or RCM simulations. *Clim. Change* **81:** 267–280.
103. Bloom, A., V. Kotroni & K. Lagouvardos. 2008. Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS. *Nat. Hazards Earth Syst. Sci.* **8:** 1249–1257.
104. Donat, M.G., G.C. Leckebusch, S. Wild, *et al.* 2011. Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multi-model simulations. *Nat. Hazards Earth Syst. Sci.* **11:** 1351–1370.
105. Kjellstrom, E., G. Nikulin, U. Hansson, *et al.* 2011. 21st Century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. *Tellus* **63A:** 24–40.
106. Barstad, I., A. Sorteberg & M. dos-Santos Mesquita. 2012. Present and future offshore wind power potential in northern Europe based on downscaled global climate runs with adjusted SST and sea ice cover. *Renew. Energy* **44:** 398–405.
107. Pryor, S.C., R.J. Barthelmie, N.E. Clausen, *et al.* 2012. Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. *Clim. Dyn.* **38:** 189–208.

108. Cradden, L.C., G. P. Harrison & J.P. Chick. 2012. Will climate change impact on wind power development in the UK? *Clim. Change* **115:** 837–852.
109. Nolan, P., P. Lynch, R. McGrath, *et al.* 2012. Simulating climate change and its effects on the wind energy resource of Ireland. *Wind Energy* **15:** 593–608.
110. Hueging, H., H. Rabea, K. Born, *et al.* 2013. Regional changes in wind energy potential over Europe using regional climate model ensemble projections. *J. Appl. Meteorol. Climatol.* **52:** 903–917.
111. Outten, S.D. & I. Esau. 2013. Extreme winds over Europe in the ENSEMBLES regional climate models. *Atmos. Chem. Phys.* **13:** 5163–5172.
112. Nolan, P., P. Lynch & C.P. Sweeney. 2014. Simulating the future wind energy resource of Ireland using the COSMO-CLM model. *Wind Energy* **17:** 19–37.
113. Tobin, I., R. Vautard, I. Balog, *et al.* 2015. Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections. *Clim. Change* **128:** 99–112.
114. Sterl, A., A. Bakker, H. van den Brink, *et al.* 2015. Large-scale winds in the southern North Sea region: the wind part of the KNMI'14 climate change scenarios. *Environ. Res. Lett.* **10:** 035004.
115. Reyers, M., J.G. Pinto & J. Moemken. 2015. Statistical-dynamical downscaling for wind energy potentials: evaluation and applications to decadal hindcasts and climate change projections. *Int. J. Clim.* **35:** 229–244.
116. Reyers, M., J. Moemken & J.G. Pinto. 2016. Future changes of wind energy potentials over Europe in a large CMIP5 multi-model ensemble. *Int. J. Clim.* **36:** 783–796.
117. Koletsis, I., V. Kotroni, K. Lagouvardos, *et al.* 2016. Assessment of offshore wind speed and power potential over the Mediterranean and the Black Seas under future climate changes. *Renew. Sust. Energy Rev.* **60:** 234–245.
118. Cravalho, D., A. Rocha, M. Gómez-Gesteira, *et al.* 2017. Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections. *Renew. Energy* **101:** 29–40.
119. Davy, R., N. Gnatiuk, L. Pettersson & L. Bobylev. 2017. Climate change impacts on wind energy potential in the European domain with focus on the Black Sea. *Renew. Sustain. Energy Rev.* **81:** 1652–1659.
120. Soares, P.M.M., C.A. Daniela, R. Cardoso, *et al.* 2017. Western Iberian offshore wind resources: more or less in a global warming climate? *Appl. Energy* **203:** 72–90.
121. González, A., J.C. Pérez, J.P. Díaz, *et al.* 2017. Future projections of wind resource in a mountainous archipiélago, Canary Islands. *Renew. Energy* **104:** 120–128.
122. Soria-Rodríguez, C. 2016. Marine renewable energies and the European regional seas conventions. *Climate Law* **6:** 314–335.
123. Abad, M. 2015. Mar, energía y ordenamiento jurídico: seguridad y sostenibilidad como referentes ineludibles para la estrategia de España. In *Instituto Español de Estudios Estratégicos (Ed.) Documentos de Seguridad y Defensa 67 Desafíos nacionales en el sector marítimo.* Ministerio de defensa, Secretaría general técnica, Eds.: 67–158. Accessed December 12, 2017. http://www.ieee.es/Galerias/fichero/cuadernos/DocSeguridadyDefensa_67.+pdf.
124. Hansen, S.H. 2011. Obstacles for wind energy development due to EU Legislation, South Baltic Programme. November 2011. Accessed January 1, 2018. http://www.southbaltic-offshore.eu/news/imgs-media/Legal_obstacles_for_wind_energy_due_to_EU_legislation_HSH_December_2011.pdf.
125. Schmitz, S. 2013. The use of the sea for wind energy projects. In *Shipping, Law and the Marine Environment in the 21st Century: Emerging Challenges for the Law of the Sea: Legal Implications and Liabilities.* R. Cadell & D.R. Thomas, Eds.:241–254. Oxon: Lawtext Publishing.
126. Smyth, K., N. Christie, D. Burdon, *et al.* 2015. Renewables-to-reefs?–decommissioning options for the offshore wind power industry. *Mar. Pollut. Bull.* **90:** 247–258.
127. Scovazzi, T. & I. Tani. 2014. Off-shore wind energy development in international law. In *International Law and Changing Perceptions of Security*. J. Ebbesson, M. Jacobsson, M.A. Klamberg, *et al.* Eds.: 244–258. Leiden, Boston. Brill Nijhoff Publisher.
128. Long, R. 2014. Harnessing offshore wind energy: legal challenges and policy conundrums in the European Union. *Int. J. Mar. Coast. Law* **29:** 690–715.
129. European Commission. 2010. Legal and socio-economic studies in the field of the integrated maritime policy for the European Union. Study on the economic effects of maritime spatial planning: final report. April 2010. Accessed January 8, 2018. https://ec.europa.eu/maritimeaffairs/sites/maritimeaffairs/files/docs/body/economic_effects_maritime_spatial_planning_en.pdf.
130. Blake, K.M. 2013. Marine spatial planning for offshore wind energy projects in the North Sea: lessons for the United States. PhD dissertation. University of Washington, Seattle.
131. Toke, D. 2011. The UK offshore wind power programme: a sea-change in UK energy policy? *Energy Policy* **39:** 526–534.
132. European Commission. 2011. EU guidance on wind energy development in accordance with the EU nature legislation. 2011. Accessed January 1, 2018. http://ec.europa.eu/environment/nature/natura2000/management/docs/Wind_farms.pdf.
133. European Commission. 2014. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Blue Energy. Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond. January 20, 2014. Accessed February 4, 2018. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0008&from=EN.
134. Wright, G., A.M. O´Hagan, J. de Groot, *et al.* 2016. Establishing a legal research agenda for ocean energy. *Mar. Policy* **63:** 126–134.
135. Gibson, E. & P. Howsam. 2010. The legal framework for offshore wind-farms: a critical analysis of the consent process. *Energy Policy* **38:** 4692–4702.

136. Scarff, G., C. Fitzsimmons & T. Gray. 2015. The new mode of marine planning in the UK: aspirations and challenge. *Mar. Policy* **51:** 96–102.
137. Snyder, B. & M.J. Kaiser. 2009. Offshore wind power in the US: regulatory issues and models for regulation. *Energy Policy* **37:** 4442–4453.
138. Fitch-Roy, O. 2016. An offshore wind union? Diversity and convergence in European offshore wind governance. *Climate Policy* **16:** 586–605.
139. Danish Energy Agency. 2018. Procedures and permits for offshore wind parks. Accessed January 8, 2018. https://ens.dk/en/our-responsibilities/wind-power/offshore-procedures-permits.
140. Marine Scotland. 2012. Marine Scotland Licensing Consents Manual, covering marine renewables and offshore wind energy development. October 2012. Accessed December 14, 2017. http://www.gov.scot/resource/0040/00405806.pdf.
141. Mani, S. & T. Dhingra. 2013. Critique of offshore wind energy policies of the UK and Germany—what are the lessons for India. *Energy Policy* **63:** 900–909.
142. Ocean Energy Forum. 2016. Ocean energy strategic roadmap. Building ocean energy for Europe. November 2016. Accessed December 7, 2017. https://webgate.ec.europa.eu/maritimeforum/sites/maritimeforum/files/OceanEnergyForum_Roadmap_Online_Version_08Nov2016.pdf.
143. Wright, G. 2014. Strengthening the role of science in marine governance through environmental impact assessment: a case study of the marine renewable energy industry. *Ocean Coast. Manage.* **99:** 23–30.
144. Netherlands Enterprise Agency. 2015. Offshore wind energy in the Netherlands. January 2015. Accessed February 1, 2018. https://www.rvo.nl/sites/default/files/2015/03/Offshore%20wind%20energy%20in%20the%20Netherlands.pdf.
145. Vázquez, A., S. Astariz & G. Iglesias. 2015. A strategic policy framework for promoting the marine energy sector in Spain. *J. Renew. Sustain. Energy* **7:** 061702.
146. Shariat, S., H.K. Müller, M. Gibescu, *et al.* 2015. The legal and economic impacts of implementing a joint feed-in premium support scheme on the development of an offshore grid. *Renew. Sust. Energy Rev.* **45:** 263–277.
147. Wind Europe. 2015. Design options for wind energy tenders. December 2015. Accessed February 4, 2018. file:///I:/24-10-2017/Paper%20Revisión%20Europa.%20Emplazamientos%20Europeos/EWEA-Design-options-for-wind-energy-tenders.pdf.