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Masterarbeit

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Development of a Methodology for Preliminary Site Assessment for Offshore Wind Applications based on ERA5 Reanalysis Data

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Development of a Methodology for Preliminary Site Assessment for Offshore Wind Applications based on ERA5 Reanalysis Data

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Zusammenfassung

Name des Studierenden
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Thema der Masterarbeit
Entwicklung einer Methodik zur vorläufigen Standortbeurteilung für Offshore-Wind Anwendungen basierend auf dem meteorologischen Reanalyse-Datensatz ERA5

Stichworte
Offshore Windenergie, Standortbeurteilung, meteorologische Reanalyse, ERA5, Software-Entwicklung

Kurzzusammenfassung

In dieser Arbeit wird eine Methodik zur globalen, vorläufigen Standortbeurteilung für Offshore-Wind Anwendungen entwickelt. Diese Methodik basiert auf umfangreichen meteorologischen und ozeanografischen Kriterien. Die eigentliche Berechnung wird auf der Basis von Hindcast Daten aus der ERA5 Reanalyse durchgeführt.

Für die Entwicklung der Methodik wird zuerst der Stand der Technik von Standortbeurteilungen dargestellt und der Rahmen der Arbeit vor diesem Hintergrund festgelegt. Daraufhin wird die Datenbasis von ERA5 erläutert und die Kriterien der Methodik erarbeitet. Diese Ergebnisse werden dann in der Entwicklung der Methodik zusammengeführt.

Um die Methodik darzustellen, wird sie beispielhaft für drei Standorte durchgeführt: Die Deutsche Bucht, die US Ostküste und Südkorea. Auf der Grundlage der diskutierten Ergebnisse wird die Methodik überprüft.

Name of Student
Ron Scheffler

Master Thesis title
Development of a Methodology for Preliminary Site Assessment for Offshore Wind Applications based on ERA5 Reanalysis Data

Keywords
Offshore Wind Energy, Site Assessment, Atmospheric Reanalysis, ERA5, Software Development

Abstract

In this work, a methodology for global preliminary site assessment for offshore wind applications is developed. This methodology is based on a comprehensive metocean criteria set. The actual calculation is performed using ERA5 reanalysis hindcast data as the input dataset.

For the development of the methodology, the state of the art of site assessment is presented and the scope of the work defined within this frame. Hereinafter, the data basis ERA5 is described and the criteria set developed. The outcomes are combined in the methodology.

In order to present the methodology, it is applied to the three example sites German Bight, US East Coast and South Korea. The results are discussed and the methodology reviewed based on the key findings.

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I would like to thank Fraunhofer IWES for the collaboration. Especially, I would like to thank Gerrit Wolken-Möhlmann, who was a great supervisor far beyond expectations and helped me whenever I ran into a trouble spot. I would also like to thank Professor Vera Schorbach who helped me developing a fascination for metocean conditions.

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This work contains modified Copernicus Climate Change Service Information [2019].

This work uses “M_Map: A mapping package for MATLAB”, version 1.4k.

Contents

List of Figures

List of Tables

Acronyms

API	Application Programming Interface
CDS	Climate Data Store
C3S	Copernicus Climate Change Service
DNV GL	Det Norske Veritas & Germanischer Lloyd
ECMWF	European Centre for Medium-Range Weather Forecasts
EEZ	Exclusive Economic Zone
ERA5	ECMWF ReAnalysis 5
GEV	Generalized Extreme Value (Distribution)
GIS	Geographic Information System
GMAO	Global modeling and Assimilation Office (Office of GSFC)
GPD	Generalized Pareto Distribution
GSFC	Goddard Space Flight Center (Department of NASA)
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IFS	Integrated Forecast System
LiDAR	Light Detection and Ranging
MARS	Meteorological Archival and Retrieval System
Metocean	Meteorological and Oceanographical
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction (Part of NOAA)
NEWA	New European Wind Atlas
NOAA	National Centers for Environmental Information
O&G	Oil and Gas
O&M	Operation and Maintenance
OWT	Offshore Wind Turbine
POT	Peak over Threshold (Method)
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UTM	Universal Transverse Mercator (Projection / Coordinate System)
WGS	World Geodetic System
WMO	World Meteorological Organization

List of symbols

Greek characters	**Unit**	**Description**
α	[-]	GEV / Weibull calculation: scale parameter
β	[m/s] / [m]	GEV calculation: location parameter

Roman characters	**Unit**	**Description**
AEP	[GWh]	Annual Energy Production
f_i	[-]	Occurrence probability of the wind speed in wind bin *i*
H_s	[m]	Significant wave height
k	[-]	GEV / Weibull calculation: shape parameter
n	[-]	GEV calculation: number of values of *x* available
N	[-]	GEV calculation: number of considered values of *x* (here: annual maxima)
P_i	[MW]	Power production in wind bin *i*
T	[-]	GEV calculation: recurrence period (here: number of years)
T_a	[h]	Number of hours per year
T_p	[s]	Peak spectral period
V_ave	[m/s]	IEC 61400 design parameter: "Annual average wind speed at hub height"
$V_\mathrm{cut,in}$	[m/s]	Cut-in wind speed
$V_\mathrm{cut,out}$	[m/s]	Cut-out wind speed
V_hub	[m/s]	Wind speed at hub height
V_ref	[m/s]	IEC 61400 design parameter: "Reference wind speed"
x	[m/s] / [m]	GEV / Weibull calculation: evaluation variable (here: wind speed at hub height or wave height)
X_T	[-]	GEV calculation: quantile with the recurrence period *T*
y	[m/s] / [m]	GEV calculation: standardised variable

1 Introduction

The wind industry has been growing steadily over the last decades. Even though the first wind farms were built in the United States and Europe, by now, the wind industry has spreaded to regions all over the world. This is especially true for onshore wind, however, in recent history, offshore wind expansion also shifted from the European Union to other areas. In 2018, for the first time in history, China as a non-European country installed the most new offshore wind capacity in the world [1]. Besides China, new offshore wind markets emerged, mainly in the United States, Taiwan and Japan. Large wind farm projects have already been proposed in these countries. In recent history, floating wind concepts have been introduced as well. This further promotes new possible sites with large wind resources, as the largest offshore wind potential "is located in deep waters, where attaching turbines to the seabed is not practical" [1].

One of the central questions of the offshore wind industry is where to build new windfarms. The decision-making process, which describes the search and selection of new sites for offshore wind, is the "siting process" [2]. Part of this decision-making process is the evaluation of a site or an area, which is referred to as "site assessment". Site assessment analyses and evaluates different criteria in order to find rate a site in the context of other sites or areas. Different studies have developed different sets of criteria from multiple categories in order to provide the best evaluation of sites or regions regarding their offshore wind potential. Still, the existing approaches are limited to small regions. On the other hand, the few studies with a larger scope or even a global scope only assess single criteria. To the knowledge of the author, no comprehensive and global approach to offshore wind site assessment exists.

This work aims to develop a global site assessment methodology. In contrast to existing global approaches, it includes a more comprehensive criteria set. This is possible due to the availability of global reanalysis hindcast datasets, which provide numerous metocean data. In this work, the most relevant metocean parameters for offshore wind are detected and are processed to a site assessment criteria set. Based on this criteria set and the hindcast data, the methodology of this work allows to compare sites from all around the globe.

In the following chapter, common approaches for site assessment will be reviewed. This will lead to the definition to the exact scope of this work. After that, the reanalysis hindcast dataset, which forms the database for this work, will be described. The methodology will be introduced by first defining the criteria set and then describing its implementation in the actual methodology. The methodology will then be applied exemplarily to discuss its strengths, weaknesses and overall applicability.

2 Offshore Wind Site Assessment

„Site Assessment" is by no means a standardised term with an explicit meaning. It is rather used as a collective term for different methods and in different contexts, which may lead to a terminology problem. In order to prevent misconceptions, in this chapter, the term is defined for this work and different approaches to it are described.

Both the terms "site" and "assessment" have been used differently in scientific literature. "Site" can refer to areas of different sizes, for example to a single location of a wind turbine or a measuring station or – on the other hand – to an entire region. There have been attempts to distinguish between the different usages of the term. For example, A. Sempreviva et al. introduced two definitions of "site assessment" in their paper "*Review of Methodologies for Offshore Wind Resource Assessment in European Seas*": "Regional mapping" for larger sites and "micro-siting" for sites of single turbines or measuring stations [3].

The term "assessment" includes the extent and type of the site assessment methodology. It can range from a general evaluation of the wind resources to a very detailed assessment of the site, for example, the slope of the seabed. In order to prevent ambiguities, the extent and type of the assessment has to be defined clearly. This definition of the assessment is mainly determined by the set of criteria, which forms the basis for any site assessment methodology. A comprehensible site assessment methodology therefore requires a clear communication and a plausible definition of the criteria set. As site assessment is linked to the siting process, the purpose to "determine the location of future offshore wind turbines" [2], these criteria are often called "siting criteria" in scientific literature [4].

The reason why the general term "site assessment" is not standardised is that the assessment of site parameters is required at different points and under different circumstances of both scientific work and actual industrial projects. For example, in order to provide a basis or to contribute to offshore wind siting, more general assessment approaches are chosen in combination with a large scope for the site. In order to provide site details, for example for the design basis of a specific foundation at a specific site, very detailed assessment approaches are used in combination with a very small scope for the site, where this assessment is valid. In both cases, the term "site assessment" is usually explained for the project specific background to clarify the scope of the approach. For industrial projects, different stages of site assessment may be defined according to the stage of the entire project.

In summary, the different approaches to site assessment, as described, lead to different methodologies. Both a very detailed assessment of the site’s seabed prior to the foundation laying and a global assessment of offshore wind resources may qualify as “site assessment”. “Site assessment” is therefore a collective term for different types and approaches to elaborate and evaluate sites of different sizes regarding a certain purpose, as in this case: their suitability to use them for offshore wind applications. Thereby, the assessment may include both the analysis of the site itself and the interpretation of the results. In this work, no implicit statement about the assessment approach or the scope is made, when the term “site assessment” is used. It is instead used as a term for site assessment in general with regard to offshore wind applications.

In this chapter, different scientific and industrial approaches to site assessment are presented. The goal is to describe the current state of the art for offshore wind site assessment and to derive possible key findings, which are relevant for the here developed methodology, which is developed in this work. This will also provide further context to classify this work in front of related studies and approaches.

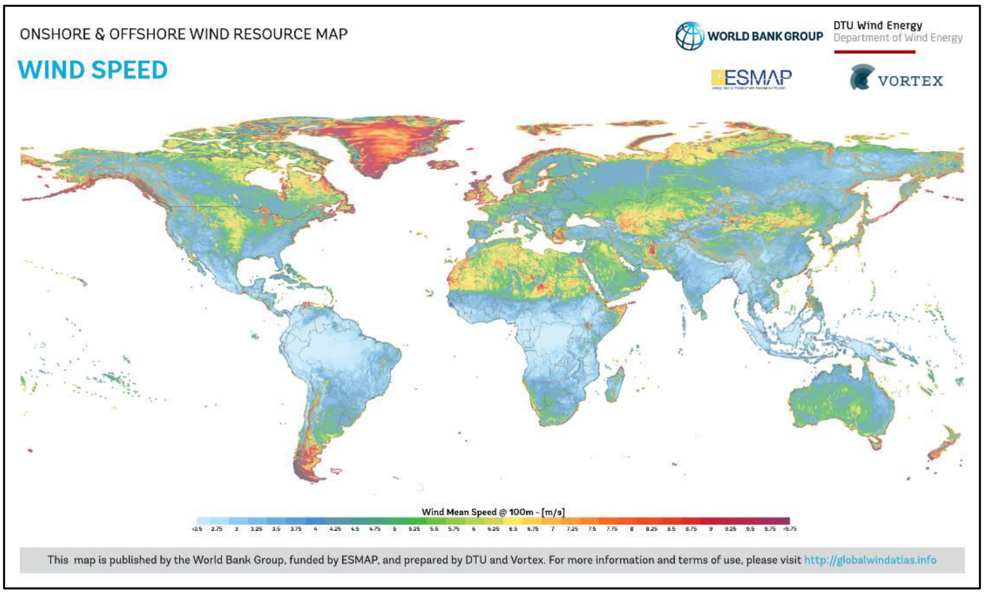
2.1 Scientific Approaches

Scientific approaches to site assessment are approaches, which aim to improve the general knowledge of the assessed site without or with small direct connection to specific industrial projects. This lack of connection to industrial projects often leads to large scopes in terms of the examined site. In addition, scientific approaches usually do not rate the results or provide in-depth interpretation of them, as they are not necessarily linked to essential decision-making processes. In contrast, scientific studies concentrate more on the actual analysis of the site. This chapter aims to provide an overview over these scientific approaches. This chapter only covers entire scientific site assessment approaches and not scientific research, which is linked to site assessment, as for example LiDAR wind measurement.

Historically, for research purposes; site assessment is often defined as the “process of quantifying the wind and weather conditions on a wind energy site” [5], only. The goal is often to contribute to offshore wind siting and to detect high potential sites. A familiar example is I.

Troen and E. Lundtang Petersen's "*European Wind Atlas*" from 1989. Its designated objective is, that "the information collected and presented in the Wind Atlas clearly identifies and documents the existence of large regions with good promise for widespread exploitation of wind resource." [6] It further "constitute[s] a foundation for the calculation energy potentials – including the siting of wind turbines – in the European Communities." [6] Different scientific approaches had similar goals and targeted sites of different sizes depending on the model data or measurement coverage. The assessment approach, however, was mainly a more general one with direct link to finance. Most often, wind resources have been analysed, as "the wind resource is one of the most important factors for the financial viability of a wind farm project." [2]

In recent history, the scientific approaches to site assessment have moved into two different directions. The first direction is the increase of the examined site size. This usually applies to efforts with a more general assessment approach. While containing a less detailed analysis or a less comprehensive set of criteria, such approaches increased the scope of the site. A prominent example is "The Global Wind Atlas 3.0", which has been released in October [7]. It provides globally applicable assessment of the wind conditions.



This map is published by the World Bank Group, funded by ESMAP, and prepared by DTU and Vortex. For more information and terms of use, please visit http://globalwindatlas.info

Figure 1: Exemplary picture of *The Global Wind Atlas*, showing the mean wind speeds at 100 m height [7]

The other direction is the improvement of the assessment methodology while still being only valid for a limited site size. Scientific studies, which expand their site assessment in these terms, try to describe the interactions between different influencing parameters in a more detailed way. An example for this is D. Vagiona and M. Kamilakis' in 2018 published paper "*Sustainable Site Selection for Offshore Wind Farms in the South Aegean – Greece*" [8]. In this work, many different parameters are included in the criteria set for the site assessment approach, for example shipping density, locations of environmental protection areas, existing infrastructure and wind resource parameters. The relative influence of each criterion is determined by a TOPSIS[1] analysis. The assessment approach is only applied to the limited site/region "South Aegean". There are numerous scientific studies, which apply similar approaches to other sites or regions [4].

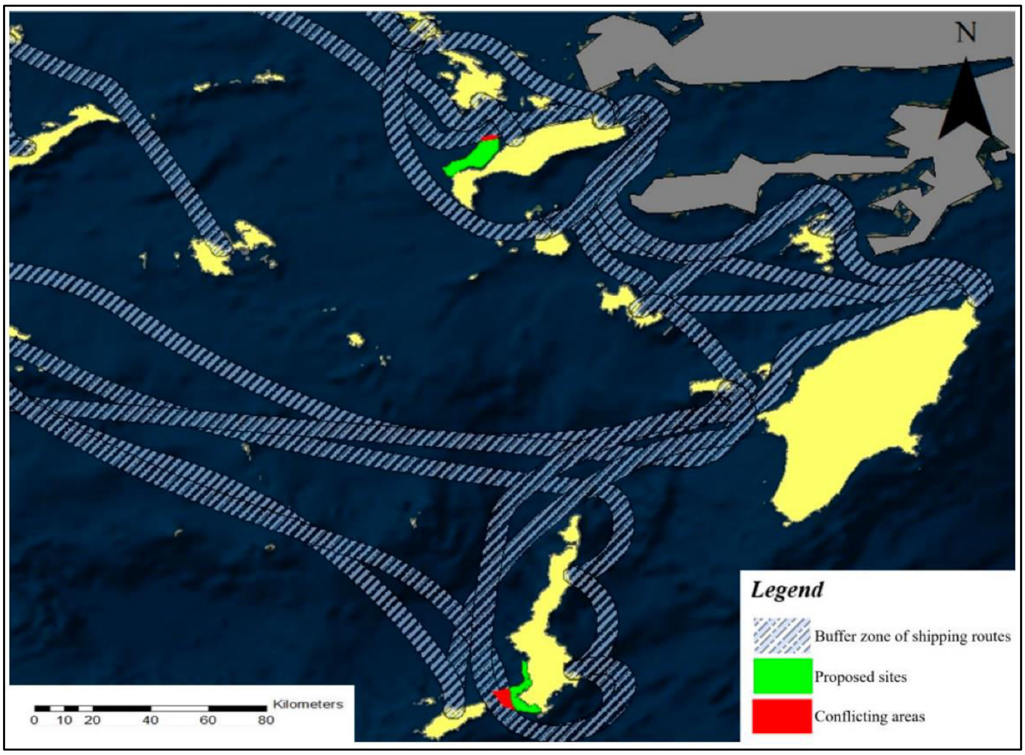


Figure 2: Exemplary picture from "Sustainable Site Selection for Offshore Wind Farms in the South Aegean – Greece", showing the effects of shipping routes on proposed sites [8]

Beside scientific approaches to offshore wind, there are several works, which indirectly evolve from or contribute to site assessment. An example is the development of LiDAR Systems in the

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[1] TOPSIS (*Technique for Order of Preference by Similarity to Ideal Solution*) is a multi-criteria decision analysis method, designed to rate single criteria in the context of other criteria.

Joint Industry Project "*IEA Wind Task 32 – Wind Lidar Systems for Wind Energy Deployment*", which aims to improve wind measurement systems [9]. Projects like this do not qualify as scientific works on site assessment specifically. However, they contribute to general scientific understanding and provide the basis for the definition standards, rules and best practices. This also facilitates site assessment.

2.2 Industrial Approaches

Industrial approaches to site assessment are approaches, which conduct site assessment for a specific industrial project and with the goal to advance its realisation. Scientific and industrial work often cannot be distinguished from each other in detail, as industrial approaches rely on scientific findings and developments. Likewise, scientific approaches relate to the industry, as their contribution to the siting process aims to locate sites for actual industrial projects. Industrial site assessment is usually conducted for a single site, the project site. The assessment is detailed, as it also aims to provide a design basis for the specific project. The site assessment is run multiple iterative times with a more detailed assessment approach each time [10]. The main goal of this industrial approach is to firstly provide planning security and secondly contribute to the design basis. Therefore, industrial approaches not only concentrate on the analysis of the site but also aim to interpret and to rate the results according to the project requirements to use them as a basis for decision-making processes.

For a specific project, the project site is often already selected, either based on more general site assessment studies or because they have been tendered. In order to provide the planning security, the site assessment approach aims to understand the site, potential problems and opportunities. For example, these types of studies aim to answer the questions, which foundation designs are possible, how the influence of a wind farm at the proposed site on environment and humans can be quantified or how financial or operative concepts have to be approached [10].

In Figure 3 the different phases to develop a final OWT design are shown including input from different stages of industrial site assessment like wind measurement, terrain conditions and turbulence.

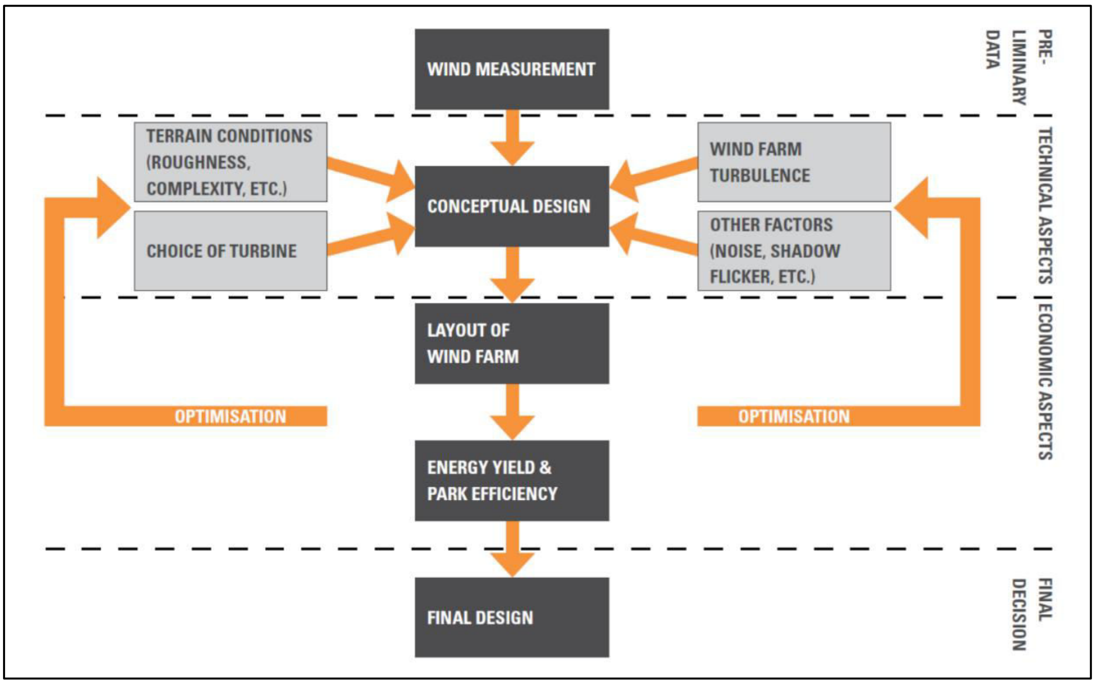

Figure 3: SGS's approach to site assessment for wind turbine design [11]

Factors, which are evaluated in a form of site assessment during an actual industrial offshore wind project, are physical parameters, like metocean conditions, as well as environmental and social parameters.

2.3 Approach of this Work

The approach of this work is defined as a globally applicable preliminary methodology for offshore wind site assessment. This methodology implements a more comprehensive criteria set for the site assessment than previous global approaches. The criteria set is based on metocean conditions.

Metocean conditions are variables from the field of meteorology, such as wind speed or wind direction, and physical oceanography, such as wave heights or bathymetry. Metocean conditions have in common that they are globally comparable, as they obviously not depend on regional rules or laws. This distinguishes metocean parameters from regional limited parameters like nature preservation rules.

The term "preliminary" refers to the extent of the criteria set. Contrary to a detailed assessment, a preliminary assessment focusses on the most important and most influential aspects of the site assessment. Therefore, a prioritisation and selection of the metocean variables is essential. As it is not trivial, which metocean conditions are most influential for the purpose of offshore wind applications, a major part of this work is the development of the criteria set.

A significant part of the methodology is the database. For this work, the reanalysis hindcast dataset ERA5 is selected. ERA5 has global data coverage and a spatial resolution close to the equator better than 31 x 31 km, which is the highest resolution among the available hindcast datasets. This resolution also determines the resolution of the site assessment methodology of this work. ERA5 provides several metocean parameters, which comply with the required data according to the developed criteria set in chapter 4 *Criteria Set*. The characteristics of ERA5, its data and its effects on this work are described in chapter 3 *Reanalysis Hindcast Data*.

The assessment approach includes the analysis of a site by calculating the criteria using the metocean variables and corresponding calculation methods. The interpretation or rating of the results is not part of the scope of this work, as the methodology is not linked to a specific project or project design. The results of the site assessment methodology of this work shall rather be applicable for offshore wind in general.

In summary, the goal of this work is a preliminary approach to global site assessment. The advantage of the preliminary approach is that a user can be provided with an overview over the different criteria for the regarded site. As no rating of the criteria is conducted in the methodology, the user can select criteria, which match the project specifications and apply them as required. In addition, it is possible to compare different sites within a larger regions and even compare them to sites of different regions. The user can utilise the results to develop a strategy or to review an existing strategy for an offshore wind application. Sites can be analysed globally with a resolution of approximately 31 x 31 km.

3 Reanalysis Hindcast Data

The reanalysis hindcast dataset ERA5 forms the data basis for the analysis of this work [12]. It provides large amounts of data for different metocean parameters. This chapter gives an overview over the relevant aspects of ERA5 in the context of this work.

In a first part, the main characteristics of ERA5 are outlined. This includes information about the applied methodology and the spatial and temporal referencing. Additionally, the parameters ‘wind’ and ‘waves’ and how they are handled in ERA5 are covered in further detail due to their relevance for offshore wind applications.

Within the second part, aspects, which made the usage of ERA5 challenging for the scope of this work, are explained as well as how they have been handled. Finally, it is addressed, why ERA5 was chosen for this work and why it was chosen over other reanalysis products.

3.1 ERA5 Characteristics

ERA5 is a global climate reanalysis dataset. It is “being developed through the *Copernicus Climate Change Service* (C3S)” [13], which was implemented by the ECMWF as part of *The Copernicus Programme*. ERA5 is open access and free to download via C3S *Climate Data Store* (CDS). It is the latest reanalysis dataset from the ECMWF and replaces ERA-Interim.

Meteorological reanalysis aims to combine theoretical, numerical models with observation data to derive hindcast and forecast data. This procedure is referred to as data assimilation. It usually relies on different observation sources and a comprehensive numerical model. In the case of ERA5, version CY41R2 of ECMWF’s *Integrated Forecast System* (IFS) was coupled with a soil model and an ocean wave model. ERA5 data was then produced using 4D-Var data assimilation [14].

The observation data, which was used for ERA5 as driving input data, consists of both satellite and in-situ data. Satellite data is obtained from multiple satellite agencies and comprises data from different sensors and measurement methods. The *World Meteorological Organization* (WMO) on the other hand provides the in-situ data. This data mainly consists of wind profiles and temperature data.

ERA5 covers the period 1950 to present. However, until November 2019 and therefore for the purpose of this work, it is available for the period from 1979 to present. Many parameters are available as short forecasts (18 hours), as well.

3.1.1 ERA5 Methodology

Until this point, the framework of ERA5 has been described. In the following chapters, the content and the methodology of ERA5 is outlined. This is done with special regards to wind and wave parameters, which are relevant for the scope of this work, i.e. offshore wind siting. A detailed analysis of the parameters and the analytical methods, as used for this work, is described in chapter 4 *Criteria Set*.

ERA5 consists of an atmospheric model, also referred to as "assimilation system", which describes the metocean state of the entire earth with physical parameters. As weather-phenomena are difficult to predict due to the complexity of the correlations among the parameters and the chaotic behaviour of the atmosphere, this atmospheric model is similarly extensive. Based on the modelled correlations, it is able to forecast the weather by simulating the parameter interaction. In addition, it can provide global metocean hindcast data. For this, observations, i.e. measurements, form the basis to assimilate the atmospheric model. This assimilation is an initial value problem. ERA5 uses observation data to "calibrate" the model using so-called *observation operators*. There are an extensive number of different observation operators for different observation types. For example, wind components use the *PPUV* observation routine, which includes wind characteristics like the logarithmic profile of wind speeds [15]. After assimilating the model state and the observation data, data can be derived from the model with temporal or spatial reference differing from the observation input.

These observations, which are used for this assimilation process, follow standardised methodologies, which allows for different and more precise processing routines [15]. For example, in-situ observations are provided by the WMO, which strictly distinguishes between the observation sources [16]. This allows ERA5 to handle observations from drifting buoys (*DRIBU*) differently than observations from mobile pilot ships (*PILOT SHIP*).

3.1.2 Spatial Reference

The spatial reference describes the exact assignment of a spatial location and is an important aspect in ERA5 data. To develop an accurate site assessment methodology, the spatial reference of the data has to be clear during all steps of the data processing. If this requirement is not met and the stored data cannot be allocated to the corresponding location, all subsequent usage of the results will be affected.

The data of ERA5 is produced and archived as either spectral coefficients or on a reduced Gaussian grid, depending on the variable. The spatial and temporal resolution of the data is existing in one high resolution (HRES) and one reduced resolution (EDA). These resolutions are defined on the reduced Gaussian grid or according to the triangular truncation of the spectral coefficients. For example, HRES refers to a triangular truncation of T369 and the resolution of a reduced Gaussian Grid of N320. This corresponds to a native resolution of 0.28125° (approximately 31 km) for HRES and 0.5625° (approximately 62 km) for EDA. Wave data has a slightly lower resolution with 0.36° (HRES) and 1,0° (EDA) [17]. The raw ERA5 data is archived on ECMWF's *Meteorological Archival and Retrieval System* (MARS). It is also copied to the CDS. There, the spatial reference is changed and the data interpolated to a regular geographic coordinate system. Both spatial references are available to download from either CDS or MARS servers.

When downloading ERA5 data, different file formats are available. In this work, NetCDF format is used. As ECMWF's NetCDF implementation only supports regular geographical grids, the above-explained interpolation is mandatory and the data will be provided with reference to a regular geographic coordinate system. Using CDS API for the download, the grid resolution is customisable. Even though the equivalent resolution for raw HRES ERA5 data is 0.28125°, ECMWF recommends to "round the resolution to 0.25 deg" [17]. Technically, it is possible to specify even a higher grid resolution; however, this "oversamples the data and does not improve the accuracy" [17].

In a regular grid, ERA5 data is provided as data points with a regular spacing between each other. For a requested grid, the retrieved data can be visualised as follows.

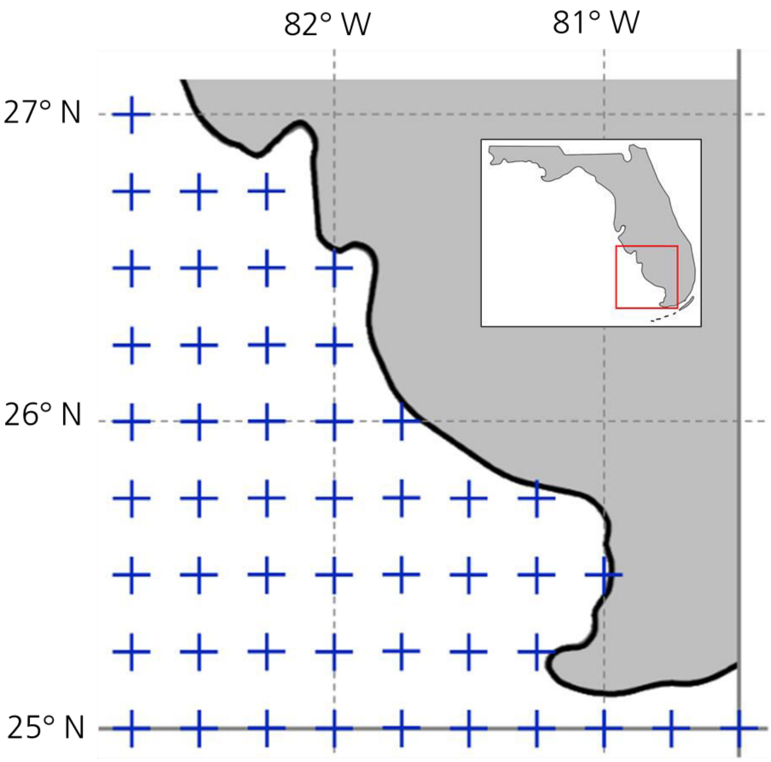

Figure 4: Visualisation of ERA5 spatial reference as data points for the example site Florida (based on [17, 18])

This plot describes the implementation of the data processing in ERA5. However, for many parameters, such as the wind speed or bathymetry, the illustration may be misleading. In contrast to standard measuring methods, ERA5 is not describing a spatially defined measurement point. Instead, the data is referencing to a grid cell. The data points, which are retrieved from CDS or MARS, describe the spatial centre of this grid cell. Depending on the parameter and its analysis method in ERA5, the value corresponding to the data point maybe an average or a sum over the entire grid cell, for example. For certain parameters, the retrieved data therefore has to be considered as follows [17].

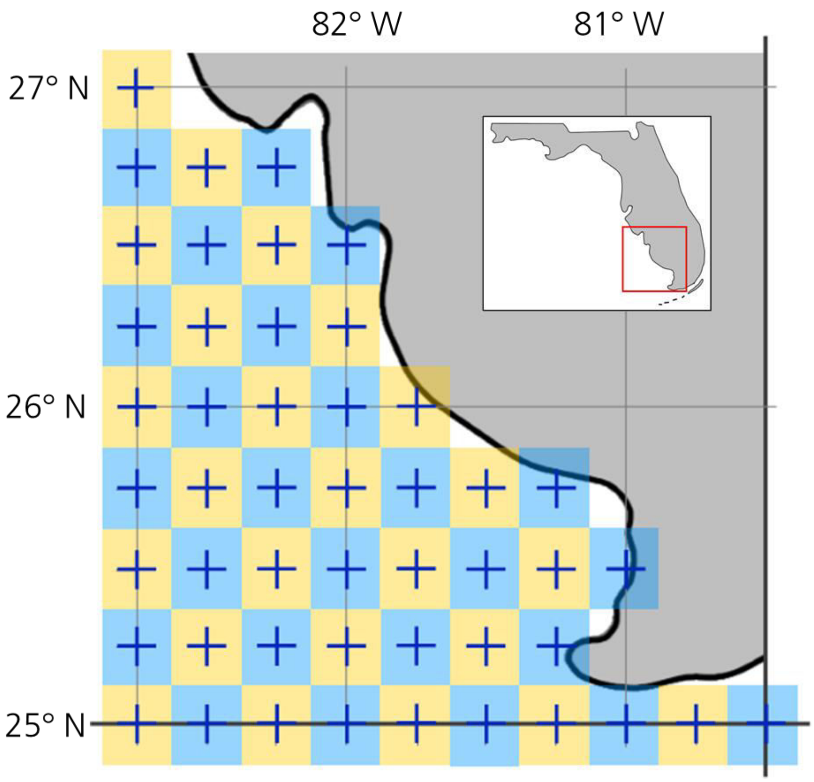

Figure 5: Visualisation of ERA5 spatial reference as a continuous tiled surface (based on [17, 18])

3.1.3 Temporal Reference

ERA5 data may be received in different temporal resolutions. For this work, HRES sub-daily data is used, which is available on an hourly basis [14]. This data allows to extract and analyse time series, which are highly representative for the investigated location due to the large amount of time covered by ERA5.

Most of the hindcast data is valid at a specified time, the validity time[1]. The parameters of this data are often referred to as instantaneous parameters. Even though they are valid at the instantaneous validity time, they cannot represent variability of the parameters on short time scales. The reason is that instantaneous parameters are provided as averages over the grid cell, as visualised in Figure 5. The average value is then calculated instantaneously at the validity

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[1] The explained characteristics explicitly do not apply to forecast data, as they are valid throughout a specified period.

time. Thus, the variability of high frequency observations on scales smaller than the grid cannot be represented by ERA5.

Apart from the instantaneous data, ERA5 contains parameters with the keywords "mean", "minimum/maximum", "accumulation" and "invariant". "Mean", "minimum/maximum" and "accumulation" all describe the respective analysis type of the parameter over a time period. "Invariant" parameters describe certain characteristics of the reviewed grid cell, which do not change over time. An example is the parameter "lake cover", which describes the proportion of the grid cell, which is covered by inland water bodies.

ERA5 provides large amounts of data for different variables. Most of these variables qualify as metocean conditions and relate to offshore wind. In particular, detailed information is provided for wind and wave conditions. As they are especially important for offshore wind, their representation in ERA5 will be reviewed in further detail.

3.1.4 Wind

Wind is the key metocean parameter to determine the feasibility of a given site for offshore wind farms. It is the source for the power production and load considerations [4]. In ERA5, wind data is mainly provided as the horizontal wind speed at 100 m height and at 10 m height. The wind speeds at these different height levels are modelled with logarithmic profile functions [19]. As 100 m corresponds to common hub heights of wind turbines, this data is well applicable without the requirement to recalculate it to a representative height considering different methodologies and estimations.

All wind speed data is provided as "instantaneous" parameters. As described in chapter 3.1.3 *Temporal Reference*, this means, that the provided data describes the model data average over the referenced grid cell. For HRES the wind speeds are therefore averaged over a grid cell of 961 km² or smaller[1]. Even though, the resolution of HRES is high compared to other publicly available reanalysis products and with regards to the global applicability, it is too low to determine microscale effects for the wind speeds. Obviously, it is therefore also not possible to distinguish between microscale and mesoscale impacts or to quantify them. In particular, this applies to turbulence phenomena. Wind turbulence is mainly caused by local obstacles or

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[1] 961 km² refers to the size of a grid cell at the equator. For other latitudes, the size of the grid cell is smaller as described in chapter 3.2 *Challenges*.

roughness changes [20]. The roughness changes are classified as microscale effects, which are restricted locally and are not covered by ERA5 HRES. Therefore, ERA5 cannot provide wind turbulence data required for offshore wind purposes.

In ERA5, wind speed data is separated into the “u” and the “v” component, describing the eastward and the northward component of the wind. Horizontal wind speeds and wind directions may be deducted from the components.

An overview over the ERA5 wind data, which is used in for the methodology of this work, is presented in *Appendix A – ERA5 Parameters*.

3.1.5 Waves

Waves are another crucial metocean condition, which affects offshore wind projects. Waves determine the loads onto the substructure of the turbines and dictate the feasibility of marine operations including installation and maintenance. ERA5 includes a comprehensive numerical wave model: the ECMWF version of the WAM[1] model. This wave model produces and archives the data on a different grid and with a different resolution to that of the atmospheric model of ERA5. However, upon downloading ERA5 data, wave data is interpolated to the grid of the atmospheric model so that all downloaded data is described by a uniform spatial reference.

The sea state is represented as a two-dimensional wave spectrum in the model, which corresponds to the full description of the wave field. It facilitates the derivation of both swell and wind waves and can further be segmented into the different partitions. All these parameters are provided separately or as combined parameter by ERA5. For example, the “Significant height of combined wind waves and swell” can be accessed as well as the “Significant wave height of second swell partition”. Besides the significant wave height, mean wave heights, individual wave heights, wave periods and wave directions are also available. This wide range of parameters sets up for a comprehensive analysis of the sea state.

As for wind parameters, wave data is available as “instantaneous” parameters.

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[1] The WAM (Wave Model) project, the first third generation wave model, was an international effort to refine numerical wave modelling [19].

An overview over the ERA5 wave data, which is used in for the methodology of this work, is presented in *Appendix A – ERA5 Parameters*.

3.2 Challenges

ERA5 provides the data basis for a global site assessment methodology. This cannot be matched by either measurement campaigns, which fail to provide global consistency, nor by global single-parameter analyses, like *The Global Wind Atlas*, which fail to provide the range of different parameters for a profound site assessment.

Even though, the content of ERA5 is matching the main requirements of this work, some of its framework also challenges the applicability of the data. These aspects of ERA5 are examined in this chapter. It is also shown that none of these challenges inhibits the application of ERA5 for this work.

Longitudinal Distances

Firstly, the spatial reference of ERA5 has to be considered. ERA5 is calculated and archived on a reduced Gaussian grid. Reduced Gaussian grids have the characteristic that the horizontal distance, i.e. the distance from one degree of longitude to another, is constant for all latitudes [21]. When ERA5 is downloaded in NetCDF-format, the grid is changed to a regular geographical grid. The data is interpolated to preserve the correct spatial reference. However, in regular geographical grids, the horizontal distance changes depending on the latitudinal location. For higher latitudes, the distance from one degree of longitude to another shrinks. At the equator, this distance is approximately 111 km, while at 60 degrees north or south, one degree of longitude equals only 56 km.

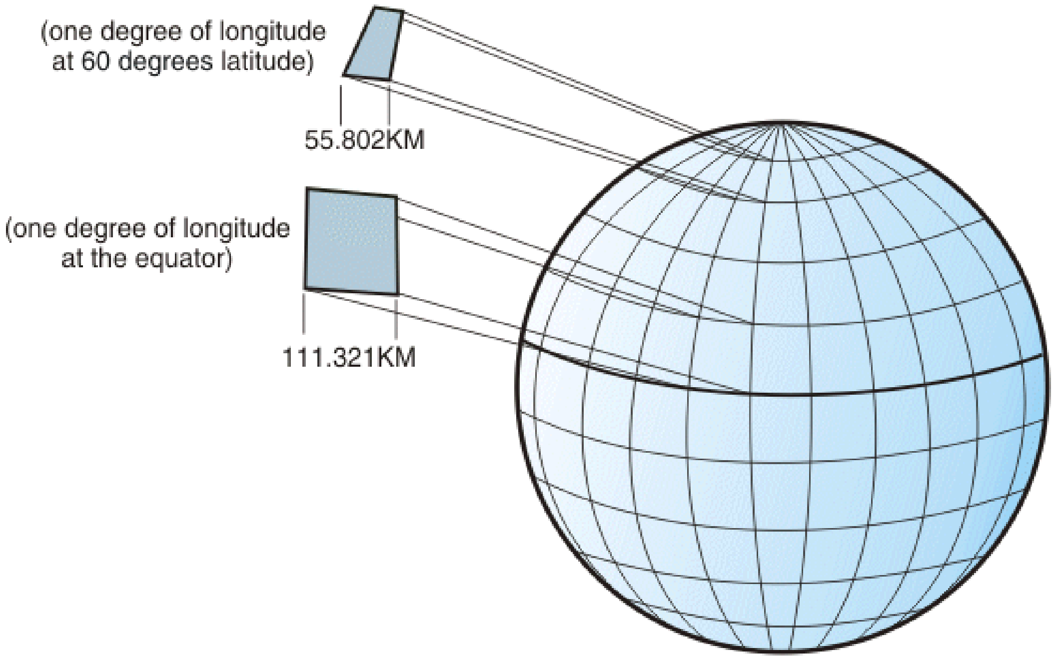

Figure 6: Different longitudinal distances based on the latitude of the reference location [22]

ERA5's spatial resolution is defined as 0.25° x 0.25° on a reduced Gaussian grid, which corresponds to approximately 31 km x 31 km. This theoretically results in a higher resolution at higher latitudes for a regular grid, as the absolute longitudinal distance from each grid point to another is reduced here. In reality, this is not the case. ERA5 oversamples the available data and creates additional grid points. These do not reference to separate or additional data and do therefore not improve the accuracy of the data [17]. This characteristic of ERA5 does not challenge its feasibility for this work, however it has to be considered when comparing sites with significantly different latitudinal coordinates.

Spatial Averaging

ERA5 output parameters are available in different forms. The form of almost all data, which is processed in this work, including wind and wave data, is named "instantaneous". The data corresponds to the average value over the grid cell which is formed instantaneously at the validity time. The exact definition of the keyword "instantaneous" is described in chapter 3.1.3 *Temporal Reference*. This leads to another challenge: The form of the instantaneous wind data of ERA5 does not conform to standardised methods. For example, for wind data, IEC 61400-3.1 "requires that all parameters […] be available as functions of the wind direction and given as 10-min averages" [23]. The standard even provides conversion tables to assimilate given data, however, these conversion tables only apply for wind speeds with different temporal averaging periods. Generally, standards are based on temporally averaged data, which references to a specific spatial location, while ERA5 data produces spatially averaged data, which references to a specific time, the validity time. The question is, whether this spatially averaged ERA5 data is comparable to temporally averaged data for the application of standardised analysis methodologies. In addition, the question arises, which averaging time-period corresponds to the averaged spatial HRES-grid cell. As there are no standardised conversion methods, ECMWF was consulted regarding this question. While affirming the first question, ERA5 science expert Paul Berrisford commented the second question as follows: "The answer is not precise. […] In practice, averaging between 10 and 30 minutes might be a reasonable choice." [24] The reason for this variation are turbulences and other wind phenomena at scales smaller than the ERA5 grid. Due insufficient information regarding these phenomena, for this work, ERA5 "instantaneous" parameters are handled as 10-min average values for the application of standards.

Wind Speed Data Accuracy

For wind data, the spatial averaging in ERA5 results in another challenging characteristic: Microscale effects of the wind are not deducible as they are averaged over the grid cell. These microscale effects are mainly determined by orography and roughness length of the terrain. In wind modelling, these effects are represented as aerodynamic roughness lengths in the logarithmic wind profile. In ERA5, wind data is averaged over a grid cell. Local roughness length changes and therefore locally lower wind speeds, for example due to a small forest, cannot be described in ERA5. For a location with a high roughness length, such as a forest or a city, the wind speeds as described in the corresponding grid cell may overestimate the actual circumstances. In contrast to that, locations with low roughness lengths, such as open fields or grassland may actually contain larger wind resources than described by ERA5. The ECMWF is well aware of this problem, stating in its documentation, that the wind modelling in ERA5 is only "appropriate over the ocean or in areas where the surface is smooth and homogeneous." In areas with major changes in the roughness lengths within a grid cell, this leads "to a low area-averaged wind speed which is not comparable to the "open-terrain" wind speed […]" [19]. Based on this, J. Olauson, who examined ERA5's capacity in wind modelling for wind energy purposes in his work "ERA5: The new champion of wind power modelling?", outlines that "using reanalyses directly for determining the mean wind speed at a site is […] not recommended" [25]. Due to these correlations, it has to be questioned, whether ERA5's wind modelling provides sufficient data for wind energy site assessment in areas with roughness changes. For this work, as it concentrates on offshore site assessment, this problem is less influential. However, in coastal regions with urban environment or other roughness changes, it has to be kept in mind that the wind resources may be underestimated by ERA5. For open sea site assessment, this problem does not influence the methodology of this work.

3.3 Summary

In the previous chapters, the characteristics of ERA5 and the resulting advantages and challenging aspects are discussed. Most of these apply to other reanalysis products as well, as they are connected to the general setup of reanalysis methodologies. In this chapter, it will be summarised, why ERA5 is chosen for this work. In addition, it will be explained why it was chosen over other reanalysis products.

ERA5 matches the key requirements for this work and is therefore an appropriate source for the methodology. Mainly, it covers the key metocean variables, which are relevant for offshore wind site assessment. Both wind and wave data are covered and provided in a form, which allows for wide analysis in accordance with common standards[1]. Additionally, it is globally consistent, which meets the scope of this work.

Besides ECMWF's ERA5 there are two other major reanalysis products: *MERRA-2* (Modern-Era Retrospective analysis for Research and Applications) from the *National Aeronautics and Space Administration* (NASA) *Goddard Space Flight Center* (GSFC)'s *Global Modeling and Assimilation Office* (GMAO) and *CFSR* (Climate Forecast System Reanalysis) from the *National Centers for Environmental Information* (NOAA) and the *National Centers for Environmental Prediction* (NCEP). In addition to these three major products, there are a number of other smaller reanalysis approaches, which have not been reviewed.

ERA5 is chosen over the other products based on practical and content-related reasons. From a practical point of view, this work is conducted in cooperation with Fraunhofer IWES, who

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[1] In chapter 4.2 *Analytical Approach* it is further shown that ERA5 provides all required input for the methodology, which was developed in this work.

already have experiences with ERA5. This experience facilitates the data processing and how challenges are met. Contentwise, all products include roughly the same parameters, with MERRA-2 lacking comprehensive sea wave data. Studies, which focus on the comparison of the three products, value the quality of the data as comparable. Small advantages are given to ERA5 regarding the comparability of the data to in-situ observations [25]. One major advantage of ERA5, however, is the high resolution with approximately 0.25° x 0.25°. MERRA-2 is produced on a 0.625° x 0.5° [26]. CFSR is technically produced on a comparable resolution like ERA5, however, the output data is only available at 0.5° x 0.5° resolution [27]. In the previous chapters, it is shown that main challenges result from the resolution. The highest possible resolution is therefore preferable. This reason, as well as Fraunhofer IWES' experience with the dataset, caused ERA5 to be chosen for this work.

4 Criteria Set

The type of the site assessment approach is mainly defined by the analysed criteria set. This criteria set is also referred to as "siting criteria" in the context of a siting process, i.e. "[the determination] of the locations of future offshore wind turbines" [2]. The criteria set consists of a number of different criteria, on whose basis the assessment of the site is conducted. A criterion comprises a measurable or calculable parameter and a specification for the interpretation of this parameter, which may be based on a specific project. This specification varies from parameter to parameter and can include, for example, a hard limitation (the information, when the criterion is considered to not be met) or a soft valuation (the information, how good the criterion is met). The definition of the criteria is important to ensure the comprehensibility of the site assessment methodology. In scientific literature, this definition is therefore always the first step when developing a site assessment methodology [8, 28–30].

In the site assessment methodology of this work, the largest possible scope in terms of the site size is chosen: global applicability. For that scope, the available number of criteria and their degree of detail are limited. This work will concentrate on metocean parameters as criteria. The goal is to include a more comprehensive set of criteria than other global approaches, such as *The Global Wind Atlas*, which includes only wind parameters [7]. The ERA5 reanalysis hindcast dataset offers globally consistent metocean parameters and will therefore form the data basis for this work. This work aims to develop a preliminary approach to site assessment for offshore wind. The criteria set is therefore developed with the goal to discover the most important and most influential metocean parameters and to convert them into criteria, which match the demands of offshore wind in general.

As these demands are heterogeneous throughout the different sectors of offshore wind, not all interpretations of the parameters are unambiguous. In order to provide a methodology to assist the demands of offshore wind in general, the criteria are chosen to be more describing in contrast to being more judging. This approach is in accordance with the goal of this work to provide a basis for site assessment rather than conducting the entire site assessment itself. It allows the user to interpret the results in a way, which suits the demands of his or her specific project.

In order to develop the criteria set with regard to metocean parameters, three steps are approached in this chapter: Firstly, the criteria fields are determined. That sub-chapter aims to detect the most relevant criteria fields for a preliminary site assessment. Basis for this is the scientific literature, which shows a current state of the art when approaching preliminary siting procedures. In addition, it is clarified, which criteria fields have been determined as highly relevant in existing scientific site assessment studies.

Secondly, the exact criteria set is developed. From the criteria fields, single criteria are formulated. It is then determined, how these specific criteria are calculated and whether this calculation is possible based on the provided data in ERA5. Basis for this are international standards, which define both the key parameters for offshore wind applications and possible calculation approaches.

In a third step, the proposed criteria set is validated. Industry partners are consulted for this matter. The industry partners are chosen based on their expertise in key parts of offshore wind projects: Fraunhofer IWES for turbines, Ramboll Deutschland GmbH for offshore foundations and Equinor ASA for marine operations with reference to offshore wind. These industry partners have evaluated the proposed criteria set. Based on their knowledge of additional demands for actual offshore wind projects, they complemented the criteria set.

In the end, the final criteria set is presented.

4.1 Criteria Fields

In this chapter, the metocean criteria fields are determined based on scientific studies with a comparable scope to this work. The comparability is defined as follows: Studies shall conduct site assessment with reference to offshore wind siting. Studies, which concentrate on the extensive analysis of single sites, are not included. The studies shall apply a criteria set and not base their site assessment methodology on single parameters. Finally, the applied criteria set shall include metocean conditions. Site assessment studies with a focus on social or political issues, only, are not reviewed. From the resulting studies, criteria fields are derived.

Examples for reviewed studies are „*Review of Offshore Wind Energy Assessment and Siting Methodologies for Offshore Wind Energy Planning in Malaysia*“ by L. Ho et al. [28], „*Multi criteria decision analysis for offshore wind energy potential in Egypt*“ by M. Mahdy [29] or

"*Multi-criteria selection of offshore wind farms: Case study for the Baltic States*" by A. Chaouachi et al. [30]. Due to the numerous different studies, a complete and scientifically profound quantitative review of the criteria sets is not possible within the scope of this work. A similar work was conducted by Ho et al. did exactly this in 2018 in their study "*Developing offshore wind farm siting criteria by using an international Delphi method*" [4]. Therefore, the results of Ho et al.'s study will be the main basis for the criteria field development.

Ho et al. define criteria fields organised in four categories: profitability, social, security and environment. As different studies use different wording for similar criteria, Ho et al. determined generic terms for the criteria fields. They present all different criteria fields and classify them. This was achieved by asking 15 experts from the wind industry from different countries to evaluate different criteria fields and their relevance for the offshore wind siting process. Based on this evaluation, all criteria fields were assigned with corresponding percentages to the scale "unimportant – somewhat important – important – very important – extremely important".

Metocean parameters, which are all assigned to the category "profitability", are rated as the most important ones. The highest rated criteria field is "wind speeds & directions" with an average of 64% of the votes reaching "extremely important". The second highest criteria field is whether "collaborative planning and stakeholder involvement" has taken place during the siting process with 50%. The third highest ranked criteria field is again a metocean parameter: the bathymetry. The criteria field is named "suitable depth for a wind turbine foundation" and is rated with an average of 43% as "extremely important". Beside these three criteria fields, no criteria field has the majority of the votes in the area "extremely important". Among those with the majority of the votes at "very important", metocean conditions are again very highly rated: "Distance to grid/shore"[1] (21% extremely important, 50% very important) and "Ocean waves challenging offshore wind farm construction and maintenance" (35% very important, 35% important). Apart from those, criteria fields from the category "environment" and criteria fields relating to conflicting economic activities (shipping, fishing, O&G) as well as financing are rated highly. The only criteria field relating to metocean data, which was not rated as highly important, is "soil conditions" which is rated predominantly as "somewhat important".

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[1] The distance to the shore is a geographical parameter and not necessarily a metocean condition. However, it is directly linked to metocean conditions and influences OWF in a similar way, especially in terms of marine operations [31]. It is obviously a globally consistent parameter and will be treated as a metocean condition for the remainder of this work.

Based on the results of Ho et al.'s study and the applied criteria of site assessment studies, which were not included in Ho et al's analysis, four metocean criteria fields are identified for this work:

1. *Wind characteristics, especially velocities and directions*
2. *Wave characteristics*
3. *Bathymetry*
4. *Distance to the shore*

4.2 Analytical Approach

In this chapter, the development of specific criteria from the criteria fields is described. The criteria fields themselves do not qualify as criteria, as they do not describe measurable or comparable parameters. To define the specific criteria, two conditions have to be met. Firstly, the criteria have to be relevant, which means that they are connected to the requests of the offshore wind industry. The scope of this work – a preliminary site assessment methodology – further demands to cover only the most important of these relevant criteria. Secondly, the calculation method of the criteria cannot be chosen arbitrarily. This means that the calculation methods have to be based on state of the art knowledge in order to be relevant.

To meet these to requirements, the main basis for the definition of the criteria is the international standard IEC 61400. This standard is published by the *International Electrotechnical Commission* (IEC) and covers guidelines for the design of wind turbines for the industry. Therefore, both the selection and the calculation methods of the covered parameters in this standard are highly relevant and verified for the offshore wind industry. Part 1 (IEC 61400-1) covers general information for the wind turbine design and also the assessment of "External Conditions" [32]. Part 3.1 complements the requirements of Part 1 with additional parameters for fixed bottom offshore wind [23]. Part 3.2 further complements the requirements for floating wind [33]. These three parts of the IEC 61400 combine all relevant parameters for the design of offshore wind turbines.

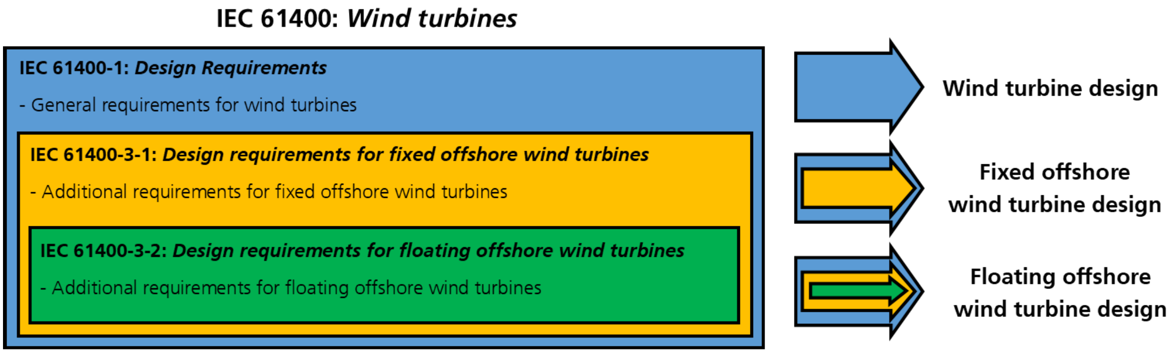

Figure 7: Visualisation of IEC design requirement sources for different wind turbine applications

In this work, requirements from all the three parts are referred to as "IEC 61400 requirements". Only in cases of direct quotations, the specific part is mentioned.

The consideration and assessment of external conditions (i.e. metocean conditions) in IEC 61400 is separated into two parts. The first consideration is during the design requirements. As wind turbines are usually not designed for a specific site, the significant parameters wind speed and turbulence are combined to a "Wind Turbine Class". According to IEC 61400-1, "the intention of the classes is to cover most applications. The values of wind speed and turbulence parameters are intended to represent many different sites and do not give a precise representation of any specific site." [32] In a second step, IEC 61400 provides guidelines, how the wind turbine design can now be verified for a specific site. As the wind turbine is developed according to a previously defined Wind Turbine Class, it has to be shown for a specific site that "all these [site-specific] conditions are no more severe than those assumed for the design of the wind turbine." [32] IEC 61400 provides the necessary assessment methods for external conditions at the proposed site for this comparison. The findings of the comparison of the design basis and the actual external conditions have then to be included into the design, if necessary. The inclusion of external conditions in the wind turbine design process according to IEC 61400 is visualised in the following figure.

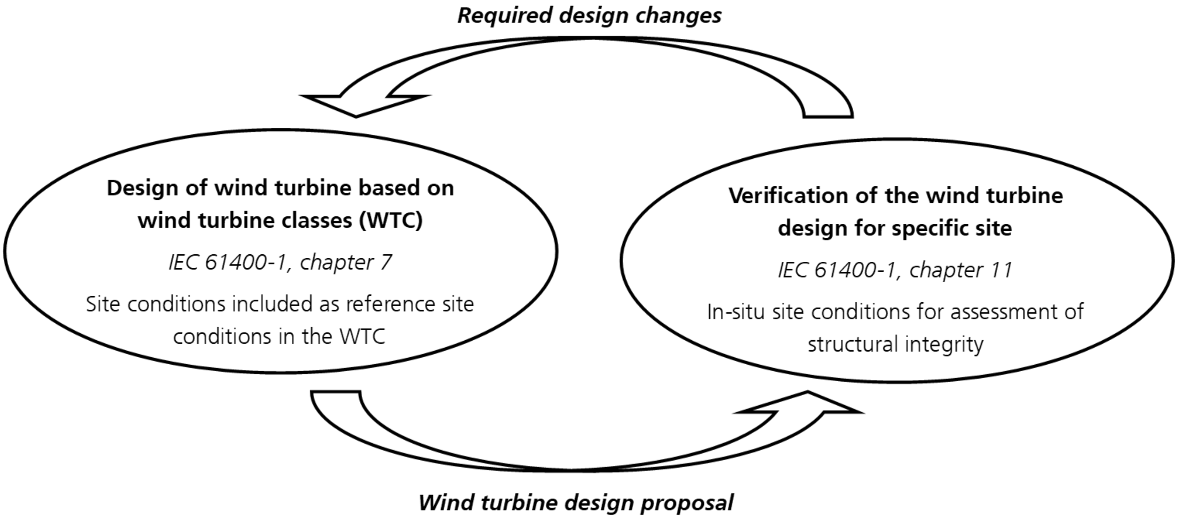

Figure 8: Iteration loop for wind turbine design as specified in IEC 61400-1

The second step provides the framework for the analysis of the metocean parameters (i.e. external conditions) in this work. In the following chapters, the criteria are formulated for the four criteria fields.

4.2.1 Wind Criteria

To assess the wind conditions for a site, the three relevant parts of the IEC 61400 define parameters. These parameters are presented in Table 1.

Table 1: Parameters required for the assessment of wind conditions at a specific site based on IEC 61400 (all parameters are defined at hub height)

Required wind parameters from IEC 61400-1 [32]	**Additional wind parameters from IEC 61400-3-1 [23]**	**Additional wind parameters from IEC 61400-3-2 [33]**
Extreme 10-min average wind speed with a recurrence period of 50 years[1, 2]	Extreme 10-min average wind speed with a recurrence period of 1 year[2]	Low-frequency range of the wind
Wind speed probability density function[1]		
Wind direction probability		
Ambient turbulence standard deviation[1]		
Flow inclination		
Wind shear		
Air density		

To apply the required parameters of the standard, IEC 61400 defines that „all parameters, except air density, shall be […] given as a 10-min average." [32] Even though, ERA5 does not support this frequency, according to the findings of chapter 3.2 *Challenges*, this precondition is considered to be met by the parameters of ERA5.

The proposed set of parameters in IEC 61400 (Table 1) provides the basis for a detailed assessment of a given site to verify the wind turbine design of an industrial project. As this

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[1] This parameter is used in IEC 61400 to verify the chosen Wind Turbine Class as design basis of the wind turbine at a given site. It is therefore especially important as it majorly determines the suitability of a given wind turbine for a particular site.

[2] The extreme 10-min average wind speed with different recurrence periods is not the extreme wind gust for the same recurrence periods. The extreme gust is usually higher than the here regarded extreme 10-min average wind speed.

work aims for a preliminary assessment of a given site, the most relevant of the proposed parameters are identified and added to the criteria set of this work. The parameters, which are chosen, are

- the extreme 10-min average wind speed with a recurrence period of 50 years,
- the extreme 10-min average wind speed with a recurrence period of 1 year,
- the wind speed probability density function and
- the wind direction probability.

The "extreme wind speed with a recurrence period of 50 years" and the "wind speed probability function" are rated highly important in IEC 61400, as they are used to verify the Wind Turbine Class as design basis for a wind turbine at the particular site. The main design variables "reference wind speed" (V_{ref}) and "annual average wind speed at hub height" (V_{ave}) are derived from these two. They are therefore included in the criteria set of this work.

In addition, the "ambient turbulence standard deviation" contributes to the Wind Turbine Class definition and is very important. However, this parameter is not contained in the ERA5 dataset. Relevant turbulence phenomena for wind turbines are primarily caused by local obstacles and roughness changes [20]. Within ERA5 grid cells of approximately 31 x 31 km, these phenomena can therefore not be described adequately. One could assume that the environmental roughness changes are negligible offshore because of the evenly flat surface of the seas. Still, the major turbulence cause is the wind farm layout (i.e. turbulence induced by adjacent wind turbines) , which cannot be described by any general type of site assessment [20]. In summary, the „ambient turbulence standard deviation" is an important factor, which can not be merged with the scope of this work. However, for any additional site assessment with a smaller spatial scope, the assessment of the turbulence should be prioritised.

The parameter "extreme 10-min average wind speed with a recurrence period of 1 year" is also included in the criteria set. Based on IEC 61400-3-1, it is the primary supplement for offshore wind applications in contrast to general offshore wind [23]. Additionally, it is used in other standards as a relevant parameter, such as the DNV-OS-J101 "*Design of Offshore Wind Turbine Structures*" [34].

The „wind direction probability" is included. The wind direction is a more detailed parameter, which does not necessarily meet the preliminary scope of this work, as it mainly influences the wind farm layout. It can provide useful additional knowledge of the site and sets up for an analysis of the wind-wave-misalignment. The wind-wave-misalignment is not required explicitly in the IEC 61400, though it is mentioned as a possibly relevant factor. It is referenced by the industry partner Ramboll GmbH, who outlined its relevance for the foundation design. This is further described in chapter 4.3 *Industrial Complements*.

The other parameters, which are mentioned in IEC 61400, are not included in the criteria set. They do not play an essential role in the further course of the standard and also – to the knowledge of the author – do not appear in studies with a comparable scope.

In the following part of the chapter, the exact calculation methods for the different parameters are described.

Extreme Wind Speeds

For the calculation of the extreme wind speeds with different recurrence periods, IEC 61400 only states that the extreme wind speeds “shall be estimated” [32] but does not provide a detailed calculation method. Based on different scientific studies regarding the calculation of extreme winds, like J.P. Palutikof et al.’s “*A review of methods to calculate extreme wind speeds*”, two “classical“ approaches to determine extreme winds are considered. These are

- the Generalized Pareto Distribution (GPD) or
- the Generalized Extreme Value (GEV) distribution.

Both distributions describe families of continuous probability distributions. The GPD is used for the estimation of extreme events with the peak over threshold (POT) method. POT counts and evaluates extreme events above a specified threshold. This takes multiple extreme events within a shorter period into consideration. However, the problem is that single events could appear multiple times in the POT statistic if the threshold was not selected carefully. To counteract this problem, multiple decisions for the application of the method have to be taken with detail and respect to the dataset [35]. Therefore, Davison and Smith state in their work “*Models for Exceedances over High Thresholds*” that POT analysis should “never be performed automatically, without the intervention of the data analyst, because failure to spot unusual features of the data could have serious consequences” [36].

A common approach to use GEV for the estimation of extreme values for wind speeds is applying the “annual maxima” method [35]. Therefore, a GEV distribution is derived from the maximum wind speed for each year[1]. From the distribution of annual extreme values, the cumulative probability of quantiles with certain return periods can be calculated. When applying the annual maxima method with the GEV, a minimum amount of data has to be available to ensure the significance of the analysis. N.J. Cook recommends in his work “*The Designer’s Guide to Wind Loading of Building Structures*” at least 20 years of data to achieve reliable results. He furthermore states that the method should not be applied with a data basis of less than 10 years [37].

For this work, the “annual maxima” method in combination with the GEV distribution is chosen to determine the wind speed extremes. ERA5 provides 40 years of data, which is sufficient to ensure reliable results. An automated approach is intended for this work, to provide the possibility of a quick application of the methodology to new sites. This does not comply with the requirements of the POT method, which has to be monitored to ensure correct execution.

The first step when using the “annual maxima” method is to model the GEV with the available data. For this matter, we suppose a number of n wind speeds x in m/s[2], from which a number N of annual maxima is used to fit the GEV distribution. Extreme value theorem states that for “sufficient long sequences of independent and identically distributed random variables […], the maxima of samples of size n, for large n, can be fitted into one of three basic families.” [35] These three families are called type 1 („Gumbel“), type 2 („Fréchet“) and type 3 („Weibull“) and are combined in the GEV. The GEV is described by the cumulative distribution function:

$$F(x) = \exp\left[-(1 - k \cdot y)^{\frac{1}{k}}\right] \qquad k \neq 0 \qquad 4.1$$

$$F(x) = \exp[-\exp(-y)] \qquad k = 0 \qquad 4.2$$

with the shape parameter k and the standardised variable y, which is defined as:

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[1] In the case of this work: „the maximum 10-minute average wind speeds for each year”.

[2] Though wind speed values are usually referred to as v or V, for the application of the GEV in this chapter, the common mathematical variable name x is used. This complies with the terminology of extreme value theory for the regarded random variable.

$$y = \frac{x - \beta}{\alpha} \qquad 4.3$$

where the variable x is again the wind speed, β the location parameter and α the scale parameter. Any GEV distribution is defined in terms of the shape, location and scale parameter. The shape parameter also determines the affiliation of the distribution to one of the three families. For negative or positive shape parameters or shape parameters equal zero, the GEV takes shape as visualised in the figure below.

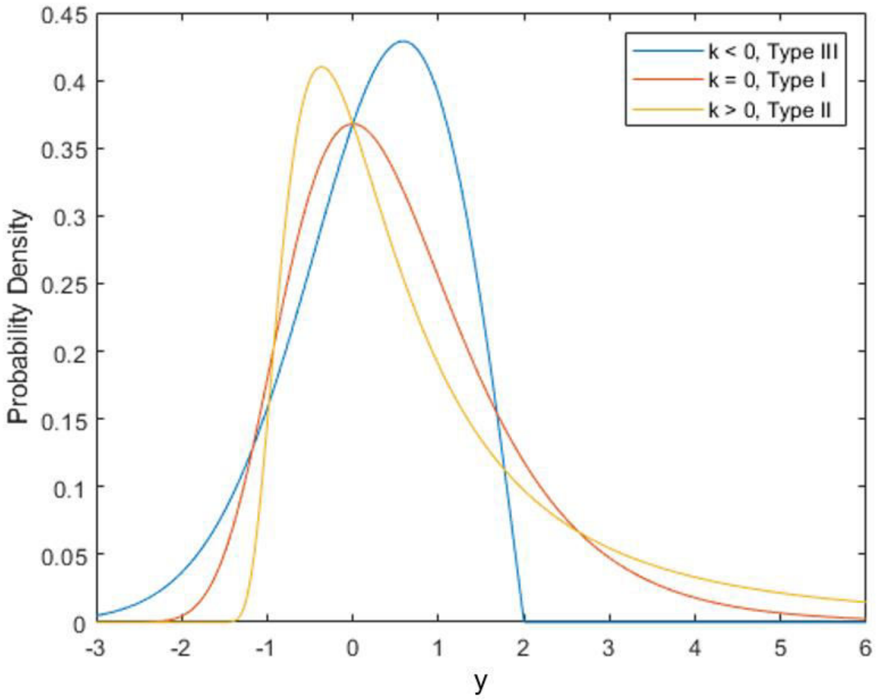

Figure 9: Generalized Extreme Value Distribution for different shape parameters (with β=1, α=0) (based on [38] and modified)

After having fitted the GEV distribution, the quantile X_T with a recurrence period of T years may be calculated by converting the probability function to:

$$X_T = \beta + \frac{\alpha}{k}\left\{1 - \left[-\ln\left(1 - \frac{1}{T}\right)\right]^k\right\} \qquad k \neq 0 \qquad 4.4$$

$$X_T = \beta - a \cdot \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \qquad k = 0 \qquad 4.5$$

For the quantile X_1 (the extreme wind speed with a recurrence period of 1 year), the formula is not applicable as it is not defined for $T=1$. However, as the GEV is defined for the "annual maxima" method, the expected value of the probability distribution corresponds to the extreme value with the recurrence period of one year. The expected value is defined by the location parameter β.

Wind Speed Probability Density Function

No exact calculation method is provided for the calculation of the wind speed probability function in IEC 61400. For this work, the two-parameter Weibull distribution is used, as referenced by common scientific literature [39]. Different standards also refer to the two-parameter Weibull distribution for wind distribution modelling. An example is DNV's Recommended Practice DNV-RP-C205, which adduces this probability distribution as the proposed method for wind distribution modelling [40].

The two-parameter Weibull distribution is a continuous probability distribution. It is described by a probability density function of the form:

$$f(x) = \frac{k}{\alpha} \cdot \left(\frac{x}{\alpha}\right)^{k-1} \cdot \exp - \left(\frac{x}{\alpha}\right)^{k} \qquad 4.6$$

Again, x is the wind speed in m/s, k is the shape parameter and α is the scale parameter. Figure 10 shows examples for the probability density functions of the two-parameter Weibull distribution with different scale parameters.

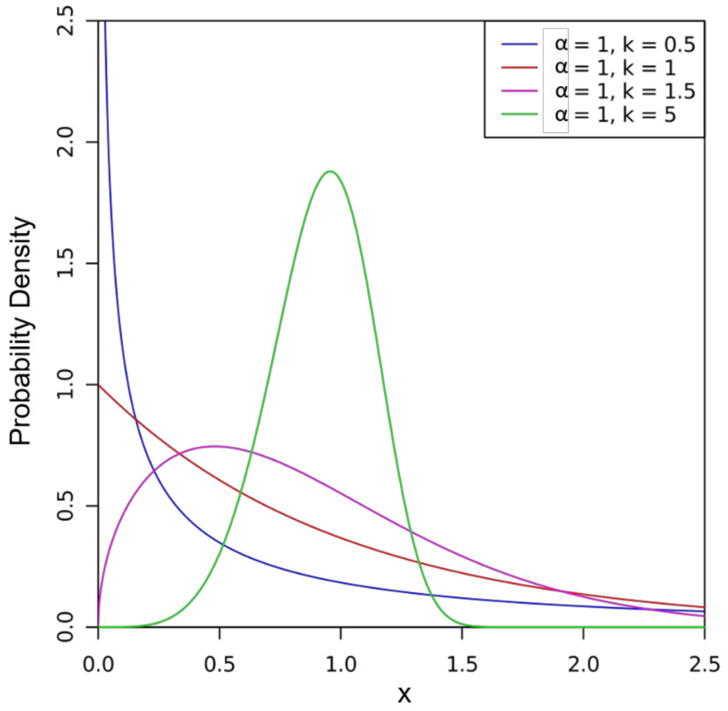

Figure 10: Two-parameter Weibull distribution for different shape parameters (based on [41] and modified)

Considering the ERA5 wind data over the entire 40 years, the wind speed probability is fitted using the two-parameter Weibull distribution to predict the wind speed probability. Such a distribution is informative for a single site (i.e. grid cell). However, it is not easily comparable in a regional overview. Here, two parameters are derived from the distribution to enable a simple regional comparison of the specified site and adjacent sites:

1. Mean wind speed
2. Expected annual energy production (AEP)

These to parameters are added to the existing criteria set. The mean wind speed is defined as the arithmetic mean of all wind speed data available in the regarded ERA5 dataset. For the calculation of the annual energy production, a generic reference wind turbine is used. Here, the 8 MW reference wind turbine of the EU programme FP7 project LEANWIND[1] is chosen. The

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[1] LEANWIND stands for "Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments" and was a EUFP7 project conducted from 2013 to 2018 under the coordination of the University College Cork.

reference turbine of this project aimed to represent a current state of the art of offshore wind turbines [42]. The following figure shows the power curve of this reference turbine.

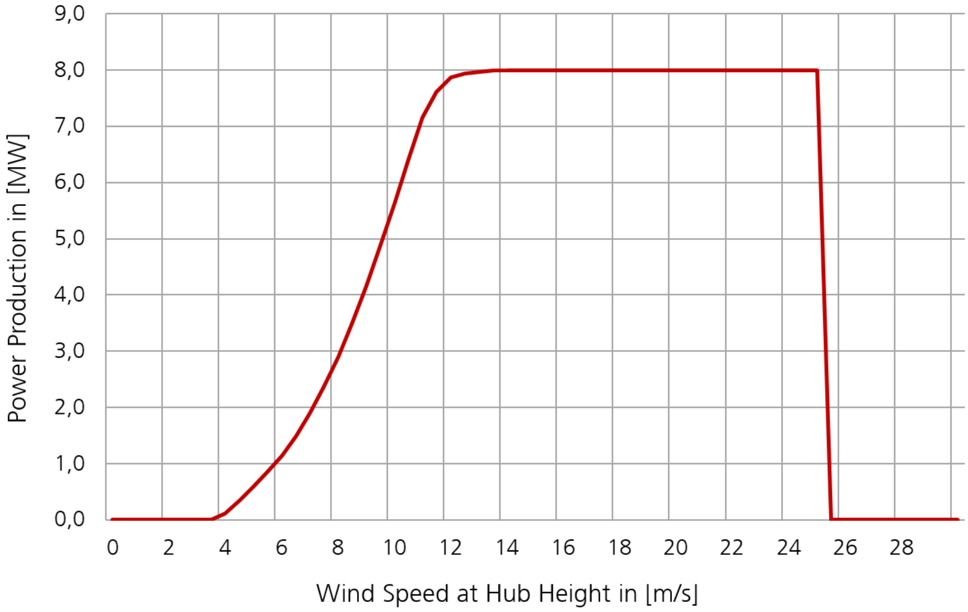

Figure 11: Power curve of the LEANWIND 8 MW reference wind turbine ($v_{cut\ in}$ = 4 m/s, $v_{cut\ out}$ = 25 m/s) (based on [42])

Based on the power curve and the wind speed probability density function, the annual energy production (*AEP* in GWh) can be estimated using the following approach:

$$AEP = T_a \cdot \sum_{i=v_{cut\ in}}^{v_{cut\ out}} P_i \cdot f_i \qquad 4.7$$

$$\sum_{i=v_{cut\ in}}^{v_{cut\ out}} f_i \leq 1 \qquad 4.8$$

with the length of a year T_a=8760 hours, the occurrence probability of a specified wind speed f_i and the power production of the reference wind turbine at a specified wind speed P_i in GW. All wind speeds between the turbine specific cut-in and cut-out wind speeds $v_{cut\ in}$ and $v_{cut\ out}$ are included as they contribute to the power production of the turbine. The combined probability of all wind speeds in this range must not exceed 100%.

The power curve of the reference wind turbine is provided in discrete steps of wind speed bins of 0.5 m/s [42]. Therefore, the theoretical approach from above is adjusted to include the averaged occurrence probabilities of the wind speeds in bins according to those of the power curve.

Wind Direction Probability

To determine the directional probability of the wind at a specified site, the possible wind directions are divided into twelve wind direction bins with a width of 30° each. The size of the wind bins is selected based on the recommendation of IEC 61400 [32]. For each time step in the ERA5 dataset, the different wind directions are then totalled for each wind direction bin. This allows a statistical evaluation of the probabilities for each wind direction bin.

4.2.2 Wave Criteria

Similarly to the wind parameters, Table 2 presents the wave parameters, which are included in IEC 61400.

Table 2: Parameters required for the assessment of wave conditions at a specific site based on IEC 61400 (with the mean wind speed at hub height V_{Hub}, the significant wave height H_s and the peak spectral period T_p)

Required wave parameters from IEC 61400-1 [32]	Additional wave parameters from IEC 61400-3-1 [23]	Additional wave parameters from IEC 61400-3-2 [33]
[-]	Significant wave height with a return period of 50 years	[-]
	Significant wave height with a return period of 1 year	
	Extreme individual wave height with a return period of 50 years	
	Extreme individual wave height with a return period of 1 year	
	Extreme crest height with a return period of 50 years	
	Long-term joint probability distribution of V_{Hub}, H_s and T_p	

In a first step, the important parameters are chosen as criteria. The chosen parameters are

- the significant wave height with a return period of 50 years,
- the significant wave height with a return period of 1 year,
- the extreme individual wave height with a return period of 50 years and
- the extreme individual wave height with a return period of 1 year.

The "significant wave height" with different return periods is included in the criteria set, as it appears in different standards for both offshore wind turbines and foundations. For example, in the DNV offshore standards for both general offshore wind structures (DNV-OS-J101, [34]) and floating structures (DNV-OS-J103, [43]) the significant wave height appears as a main parameter for the design basis to determine extreme loads.

This also applies for the "extreme individual wave height" for different return periods. For both fixed-bottom offshore wind structures and floating structures, according to the DNV-OS-J101 and the DNV-OS-J103, the individual wave height has to be regarded for the design basis [34, 43]. In IEC 61400, the wave periods associated to the extreme individual wave heights are mentioned as well. These periods are usually important for the design process and do not contribute to a preliminary characterisation of a given site. They are therefore not included in the criteria set of this work.

The parameters "extreme crest height" and "long term joint probability distribution of V_{Hub}, H_s and T_p" are not included in the criteria. The extreme crest does not provide more plain information than already provided by the extreme individual wave height. This parameter is important for a more detailed analysis of the sea state at a given site. The connection between extreme crest and individual wave height is illustrated in Figure 13. The joint probability is more important for a detailed design, as well. Additionally, it is not provided in ERA5, as the data is spatially averaged and the exact joint probability of events can therefore not be determined.

The terms "significant wave height" and "extreme individual wave height" are defined as follows. The "significant wave height" describes the arithmetic mean of the highest third of the waves of an observation as visualised in Figure 12.

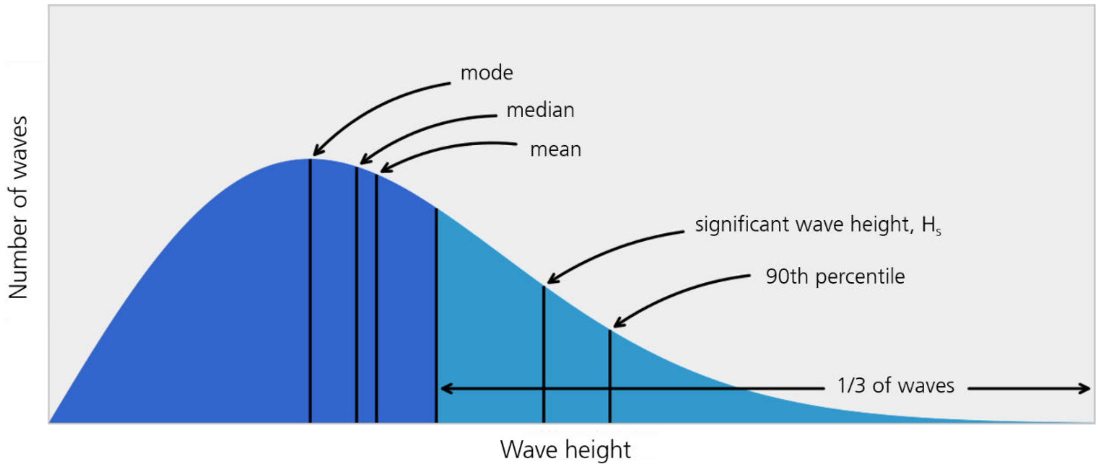

Figure 12: Exemplary statistical wave height distribution (based on [44] and modified)

The „extreme individual wave height“ is defined as the difference between the maximum surface elevation (crest) and the minimum surface elevation (trough) throughout one wave period as visualised in Figure 13.

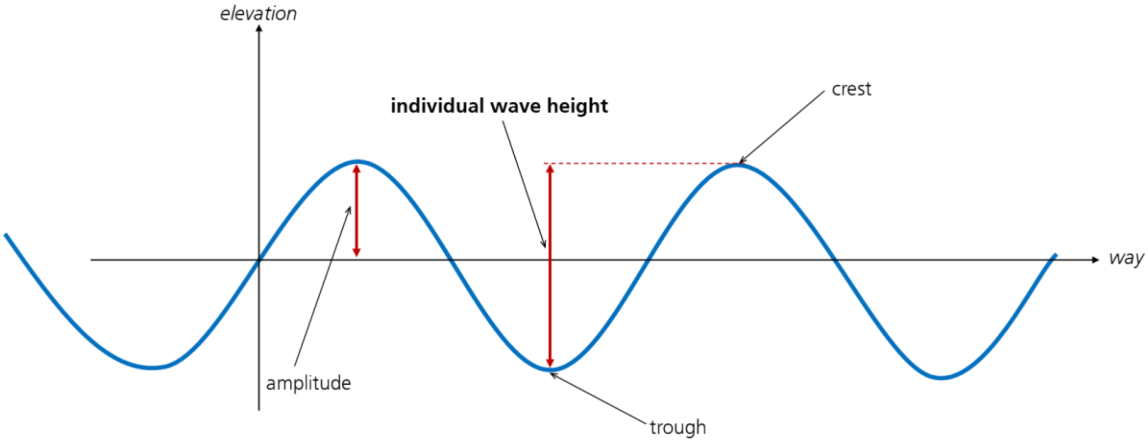

Figure 13: Wave characteristics (based on [45] and modified)

In ERA5, both the "significant wave height" and the "maximum individual wave height" are provided. The significant wave height is provided as average value over one hour of model data. The individual wave height is provided as the "expected highest individual wave within a 20 minute time window" [46] and available hourly.

In order to determine the extreme values of both significant wave height and individual wave height with different return periods, a distribution of the extreme values has to be established. According to N.V. Teena et al.'s work "*Statistical analysis on extreme wave height*", the "annual maxima" approach, as used for the extreme wind speed calculation, is a valid approach for the calculation of extreme waves, too[47]. The "annual maxima" method in combination with the GEV is used for both the determination of extreme significant wave height and extreme individual wave height.[1]

The wind and wave criteria, which are included in the criteria set, primarily affect the design of turbines and foundations. Another important sector, which is influenced by the site's metocean conditions, is marine operations. This is especially true for wave conditions, as Ho et al. name "ocean waves challenging offshore wind farm construction and maintenance" a very important criteria field for site assessment [4]. In order to include the effect of waves on marine operations in the context of offshore wind, the criterion "accessibility of the site" is added to the criteria set. This criterion is based on the DNV Offshore Standard DNV-OS-H101"*Marine Operations, General*", where marine operations are also defined by the requirement of a certain weather window [48]. The weather window is always connected to a certain marine operation. Therefore, the more general term "accessibility" is used for the criterion in this work. The accessibility is defined by a minimum time window and by a limiting variable. The time window for the criterion of this work is based on the most prominent value of DNV-OS-H101: 12 hours. The most influential limiting variable according to DNV-OS-H101 is the significant wave height H_s. Its value for the determination of the accessibility of this work is set to H_s=1.5m, which is a typical value for marine operations and is also mentioned in different DNV standards [43, 48]. The criterion "accessibility of the site" is defined as the relative amount of the time, where the variable does not exceed the limitation for a period equal or longer than the time window.

4.2.3 Additional Criteria

Beside wind and wave conditions, two criteria fields have been derived from the results of Ho et al. work [4], which qualify as single criteria for the criteria set of this work:

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[1] All formulas described for the calculation of the extreme winds also apply for the calculation of the extreme waves.

- The water depth (bathymetry) and
- the distance to the shore.

Both parameters majorly influence some more general aspects of a wind farm. The bathymetry is mentioned in IEC 61400 as an optional parameter for site assessment. It primarily determines the possible foundation concepts for a wind farm and affects the sea state at the site. The distance to shore on the other hand influences infrastructural aspects of a wind farm, like the cable laying or the possible need for an offshore transformer platform (HVDC platform). It also affects possible marine operation concepts for installation, O&M and decommissioning.

The bathymetry for each grid cell is provided by ERA5. The distance to the shore on the other hand is not provided by ERA5. In addition, ERA5 does not provide coastline data, a simple calculation of any site's distance to shore is therefore not possible. Another problem is that the size grid cells affects any precise determination of a site's distance to the shore. For example, one border of a grid cell may comply with the actual coastline. The centre of the grid cell, however, is approximately 15 km away from the shore, while the opposing border of the grid cell is even further away. Therefore, a single precise definition of the distance to shore is not possible for the spatial resolution of this work. To include an approximate value for the distance of a grid cell to the shore, the following simplified approach is used: The distance from the grid cell centre to the centre of the closest grid cell with a bathymetry of zero is calculated. This distance is used as an approximate value for the criterion"distance to the shore".

4.3 Industrial Complements

In order to validate the criteria set and to compare it to the requirements of the wind industry, industry partners have been consulted. Due to the cooperation with Fraunhofer IWES, the criteria set was developed in close collaboration. Therefore, no additional consultation of Fraunhofer IWES was conducted. Fraunhofer IWES has special knowledge for the requirements of wind turbines. These are therefore considered to be included sufficiently in the criteria set. Besides Fraunhofer IWES, Ramboll Deutschland GmbH, part of the Danish consulting engineering group Ramboll A/S and experienced in the design of offshore wind foundations, is consulted to evaluate the relevance of the criteria set for the requirements of offshore wind foundations. The input of these two is complemented by Equinor ASA, a Norwegian multinational energy company, who have reviewed the criteria set with special regards to marine operations.

All three partners confirmed the relevance of the criteria set for their section (turbine, foundation, marine operations) with regards to the scope of the work. In the following, complementary comments on the criteria set and suggested additions are summarised.

Experts from Ramboll Deutschland GmbH noted that the wind/wave misalignment is an additional important criterion for the design of offshore wind foundations, especially for foundation concepts that are hydrodynamically sensitive. The wind/wave misalignment describes how often wind and wave directions are not uniform. This wind/wave misalignment is also mentioned in IEC 61400-3-1, however, its relevance is referred to as conditional: “The importance of this influence will depend on the nature of the wind and wave directionality and on the properties of the support structure […]” [23]. As the experts rate the wind/wave misalignment as rather important, even for a preliminary assessment, it is included in the criteria set. According to IEC 61400, both wind and wave directions are evaluated in bins with a width of 30° [32]. This leads to 144 combinations of related wind and wave directions, which exceeds the scope of the criteria set. In order to outline the main information of the misalignment, the criterion “wind/wave misalignment” has been defined as the relative direction of the waves related to the wind direction. This shall be calculated in twelve bins with a width of 30° according to IEC 61400 and averaged over the entire 40 years of available ERA5 data [49].

From the experts of Equinor ASA no new criterion was introduced. However, it was mentioned that the time window for marine operations shall be adjusted. In addition to the proposed 12 hours, for marine operations in the context of offshore wind, smaller time windows of 6 hours shall be included as well. According to Equinor experts, the reason is that smaller maintenance operations usually require less than a 12-hour time window, even including transfer times. Based on this assessment, the criterion “accessibility of the site” is extended to include both a 12-hour and a 6-hour time window. This provides data for smaller marine operations as well as for larger operations like installation procedures or major repairs [50].

4.4 Criteria Presentation

In the following chapter, the final criteria set, which is used for the site assessment methodology of this work, is summarised. The criteria set is divided into *basic criteria* and *advanced criteria*. Basic criteria contain criteria, which provide single scalar values for the referenced grid cell. These criteria can easily be displayed in a map in comparison to other grid cells. Advanced criteria contain non-scalar information about a single grid cell, for example diagrams or probability functions. These criteria are better suited for the assessment of single sites rather than for a simple and quick overview or comparison. In Table 3 and Table 4, all criteria and the corresponding calculation methods are presented.

Table 3: Overview over the basic site assessment criteria of this work and a summary of the proposed calculation method

Site Assessment Criteria	**Calculation Method**
Basic Criteria	
Mean Wind Speed in [m/s]	Arithmetic mean over entire ERA5 dataset
Expected Annual Energy Production (AEP) in [GWh]	Wind speed probabilities with two-parameter Weibull distribution in combination with power curve of LEANWIND 8 MW reference WT
Extreme 10-min Average Wind Speed with a 1 year Recurrence Period in [m/s]	"Annual maxima" method with GEV distribution; location parameter
Extreme 10-min Average Wind Speed with a 50 years Recurrence Period in [m/s]	"Annual maxima" method with GEV distribution; determination of 50 year quantile
Significant Wave Height with a Return Period of 1 year in [m]	"Annual maxima" method with GEV distribution; location parameter
Significant Wave Height with a Return Period of 50 years in [m]	"Annual maxima" method with GEV distribution; determination of 50 year quantile
Extreme Individual Wave Height with a Return Period of 1 year in [m]	"Annual maxima" method with GEV distribution; location parameter
Extreme Individual Wave Height with a Return Period of 50 years in [m]	"Annual maxima" method with GEV distribution; determination of 50 year quantile
Accessibility of the Site based on a ≥12 h Time Window for $H_s < 1.5$ m in [%]	Comparison of data, which meets the requirements, with available ERA5 data
Accessibility of the Site based on a ≥6 h Time Window for $H_s < 1.5$ m in [%]	Comparison of data, which meets the requirements, with available ERA5 data
Bathymetry in [m]	Provided in ERA5
Distance to the Shore in [km]	Distance to closest grid cell with a bathymetry of "0 m"

Table 4: Overview over the advanced site assessment criteria of this work and a summary of the proposed calculation method

Site Assessment Criteria	**Calculation Method**
Advanced Criteria	
Wind Speed Probability Density Function	Wind speed probabilities with two-parameter Weibull distribution
Wind Rose (Wind Direction Diagram)	Calculation of wind directions; determination of statistics
Wind/Wave Misalignment	Comparison of wind and wave directions; determination of statistics

The proposed criteria set can be evaluated for any site with the available data from the hindcast dataset ERA5.

The criteria set does not only provide the basis for a comprehensive preliminary site assessment. With the exception of wind turbulence data, it provides the required data to validate the structural integrity of a wind turbine and the chosen Wind Turbine Class (design basis) according to IEC 61400: "It is possible to complete the assessment of structural integrity by comparison of the wind parameter values for the site with those used in the design." [32] The IEC 61400 design parameter V_{ref} is validated by comparing it to the extreme wind speed: "[…] site estimate of extreme 10-min average wind speed at hub height with a recurrence period of 50 years shall be less than V_{ref}" [32]. Additionally, "the site value of the probability density function of V_{hub} shall be less than the design probability density function […] at all values of V_{hub} between the wind speed 0,2 V_{ref} and 0,4 V_{ref}" [32], with V_{hub} being the wind speed at hub height.

The possibility, to be able to apply the results of a site assessment with the proposed criteria set to the primary validation methods of IEC 61400, further underlines the relevance of the selected criteria in this work.

5 Methodology

In the previous chapters, the goal of this work is defined: The development of a methodology that provides the basis for a comprehensive preliminary site assessment. The site assessment approach is defined by the criteria set, which is described in chapter 4 *Criteria Set*.

In this chapter, the implementation of the criteria set in a superordinate methodology is described. This covers the different components of the methodology and its structure. In a first step, an overview over the methodology is provided. The methodology consist of three main structural components, which are described in further detail; the *pre-processor*, the *solver* and the *post-processor*. In addition, inputs and outputs are defined for both the overall methodology and for the three main structural components at the interfaces.

The computing environment, which was used to implement the methodology is MathWorks' "Matlab R2012b" [51]. The developed methodology is compatible to later Matlab versions.

5.1 Methodology Overview

The methodology of this work is summarised in this chapter. The input and output for the overall process are defined and the main components are presented and classified within the methodology. In Figure 14, the methodology and the flow of information in-between the main components is visualised.

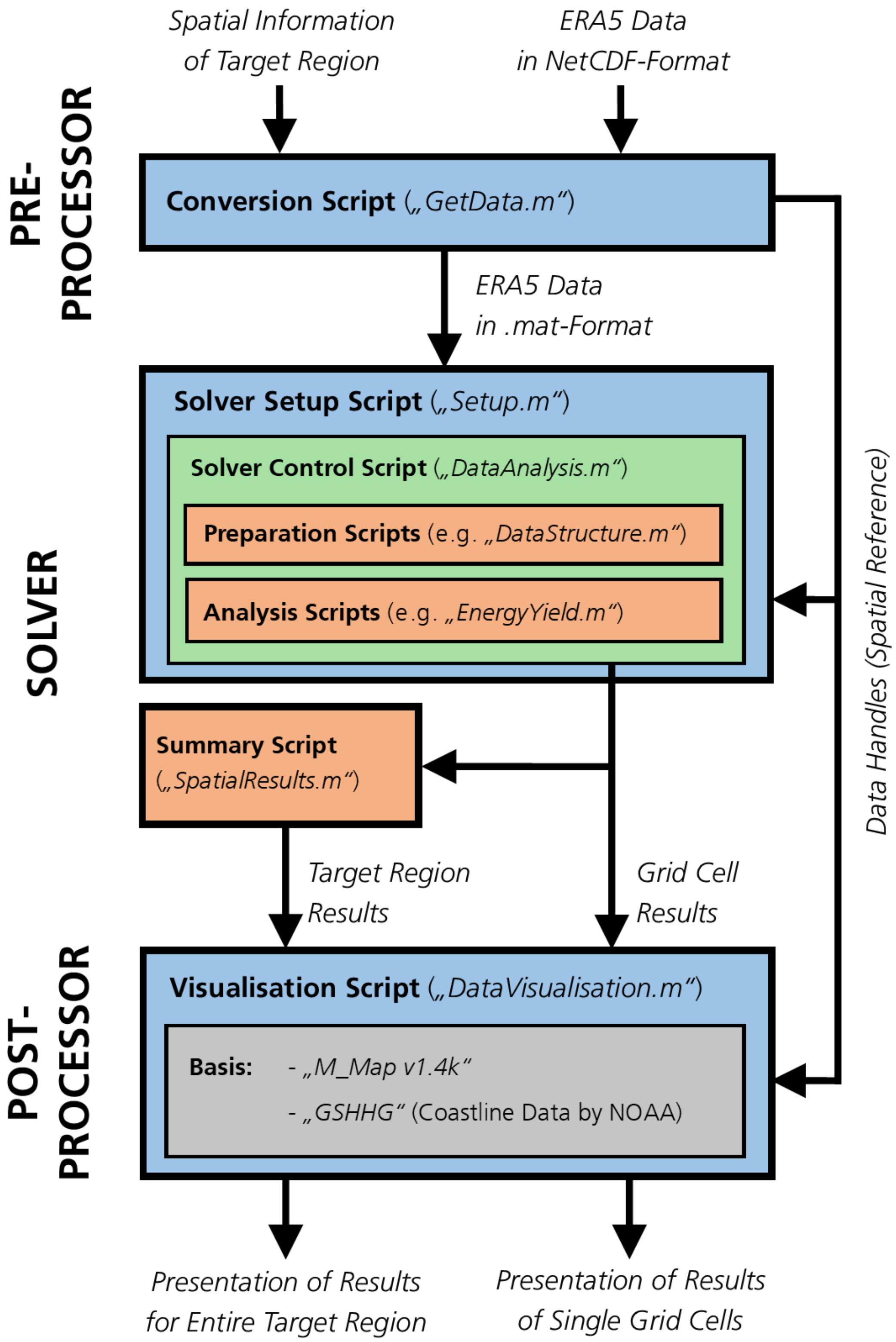

Figure 14: Overview over the methodology of this work

The input for the methodology is the ERA5 hindcast dataset. ERA5 data is available as time series with spatial references. They are obtained via Copernicus CDS API using Python scripts, which are provided by Fraunhofer IWES. Data is available in NetCDF format, which was developed for scientific data in binary format. For downloading ERA5 data from the Copernicus servers, the request is defined for target area (spatial basis), target time period (temporal basis) and target parameters (data basis). Here, the downloaded files contain one month of data with all parameters over the entire target area. For this work, 40 complete years of data are used from 1979 until 2018[1]. The data is downloaded and processed at the highest possible spatial and temporal resolution (HRES)[2]. This corresponds to a spatial resolution of approximately 31 x 31 km and hourly data. An overview over the ERA5 variables, which are downloaded and processed within the methodology of this work, is presented in *Appendix A – ERA5 Parameters*. Beside the "raw" ERA5 dataset certain information is required describing the target region.

The output of the methodology is specified, considering by the goal of this methodology to support preliminary site assessment. Besides providing the "raw" data results for the criteria, the methodology is supposed to visualise the results as well. To visualise the results for the entire target regions, the scalar results based on the *basic criteria* are visualised on maps using a GIS (geographic information system) tool. These figures display spatially arranged information to enable a basic assessment "at first sight". By using equal scales for different figures, a basic comparison between different regions is possible as well. For the assessment of a single site within the target region, the *advanced criteria* are used. All *advanced criteria* are visualised in separate figures, for example wind roses for the wind direction probabilities and wind speed probability functions for the expected wind speeds. For the assessment single sites, the basic criteria are provided as well in tabular form.

The methodology is computed using a pre-processor, a solver and a post-processor. The centre of the methodology is the solver, which assesses the pre-defined sites according to the criteria set. The calculations are implemented based on the calculation methods, which are defined in chapter 4 *Criteria Set*. The solver requires the ERA5 input data in a specified format, which is not equivalent to the NetCDF-format of the "raw" ERA5 data. The conversion of the data and its preparation is the task of the pre-processor. The solver saves its results in a specific format.

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[1] This corresponds to 480 NetCDF-files for requested target area.

[2] The exact definition of HRES can be found in chapter 3.1 *ERA5 Characteristics*.

The post-processor's task is therefore to sort the results and to visualise them. The resulting data is here transformed into figures, tables and diagrams.

In the following, these three main components are described in further detail.

5.2 Pre-Processor

The task of the pre-processor is to extract the information of the target region or site from the "raw" ERA5 data and transform it into a format, which can be accessed by the solver. Therefore, the pre-processor requires information about the target region and – to a certain limit – also information about the targeted time period, which shall be processed. The solver requires spatially arranged data; one file has to contain the various time series for a single grid cell but for the entire time period. However, the ERA5 NetCDF-files, which are provided by the Copernicus Servers, are arranged by time: For a downloaded area, one Net-CDF file contains all parameter time series covering one month for all grid cells in the area. Beside obtaining and transforming data, the pre-processor also creates a handle. This handle contains spatial information about the site, the transformed data and paths to files and directories which are required during the further process. In Figure 15, the approach of the pre-processor is visualised.

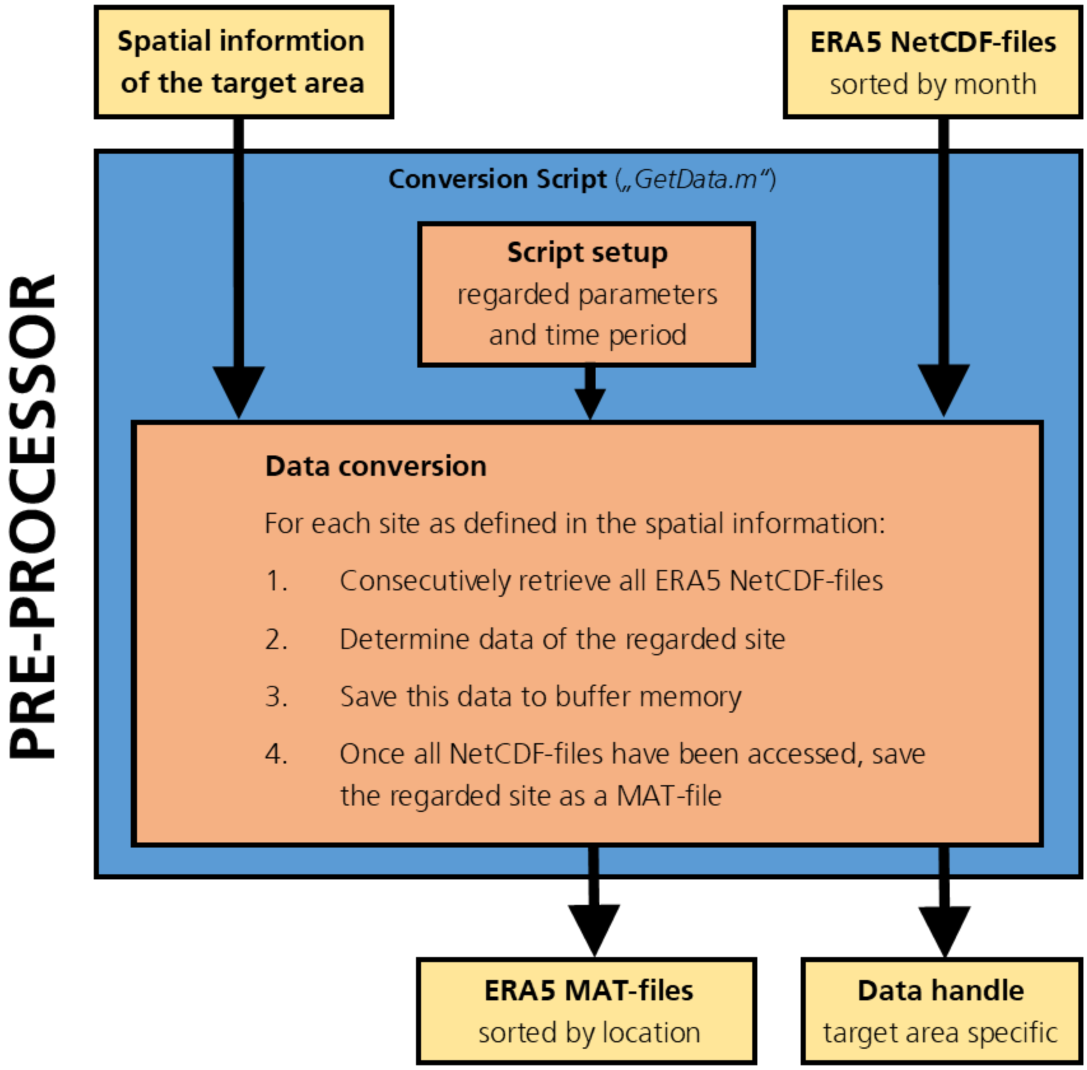


Figure 15: Visualisation of the operating principle of the pre-processor

The pre-processor consists of a single script, the *Conversion Script* "getData.m". For every site/grid cell of the pre-defined target region, all corresponding ERA5 NetCDF-files, which are included in the pre-defined time period, are retrieved consecutively. The relevant parameters of each file are copied and saved for the corresponding site. Once all monthly ERA5 NetCDF-files have been accessed for one grid cell, the retrieved data is finally saved in the Matlab format to a MAT-file, another binary file format.

5.3 Solver

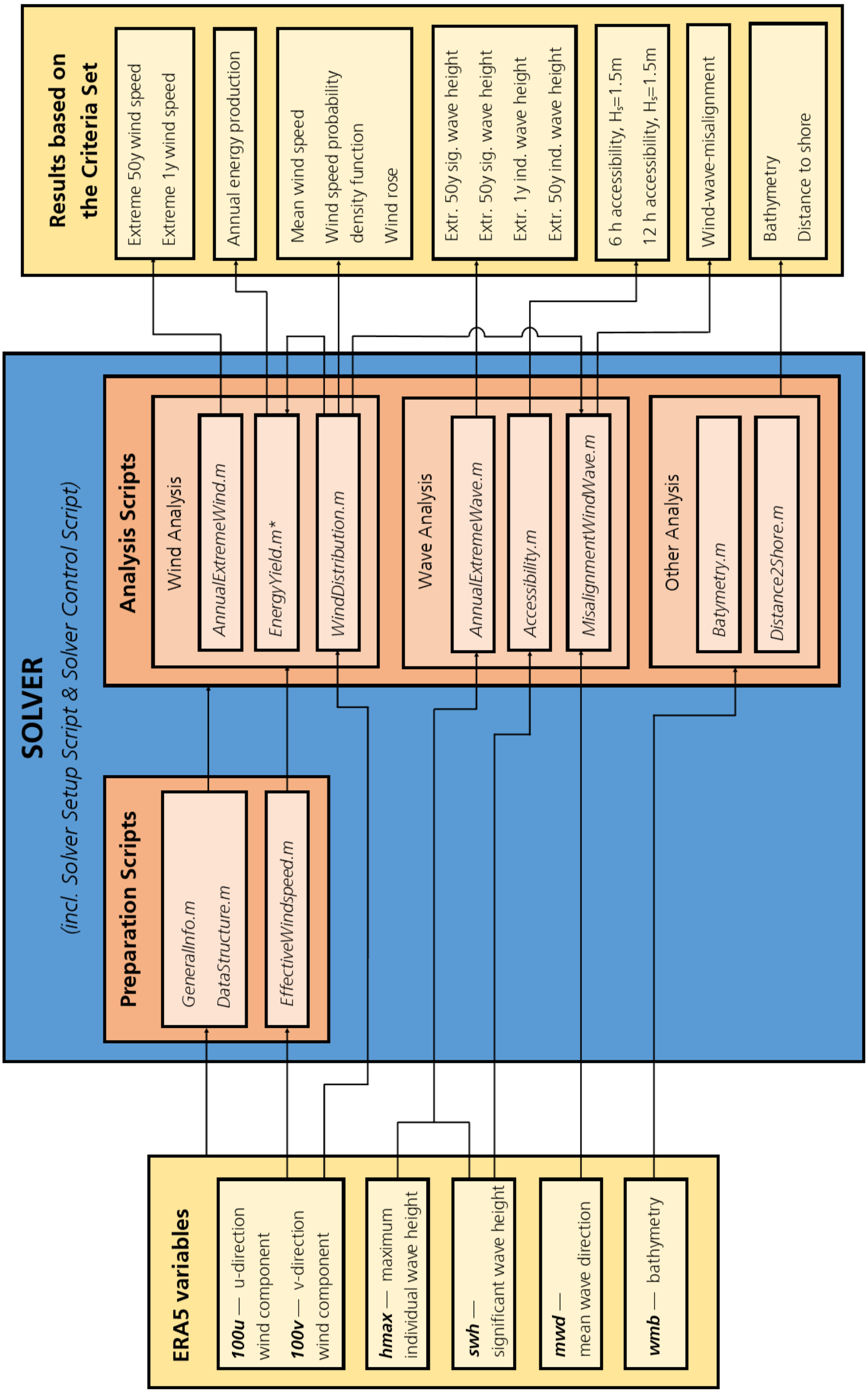
The solver is the key implementation of the methodology of this work. In the solver, the actual calculations of the criteria are conducted. Therefore, the ERA5 MAT-files are analysed and the methods are applied. The results are site/grid cell specific information, which are the basis for site assessment.

The task of the solver is to read the data time-series and to determine the criteria from the criteria set for each site/grid cell according to the handle from the pre-processor. The results will be saved in a detailed way for each site and – upon request – as a spatial overview for the entire target region. The general processing of the solver is visualised in Figure 14.

The solver consists of two parts:

1. The actual solver including the calculation of the criteria
2. The spatial sorting and summarising of the results according to the handle in the *Summary Script*

The first part consists of two nested scripts. The *Solver Setup Script* uses the handle to execute the *Solver Control Script* consecutively and automated for each site of the target region. The *Solver Control Script* executes the *Preparation Scripts* and the *Analysis Scripts* for a single site and saves the results. *Preparation Scripts* retrieve mainly structural information from the ERA5 MAT-files, which are required for the further analysis, and prepares certain time series for the further processing. The *Analysis Scripts* implements the in chapter 4 *Criteria Set* defined calculation methods to analyse the ERA5 time series. All of the different *Preparation* and *Analysis Scripts* and the flow of information between these scripts are visualised in Figure 16.



*For the calculation of the energy yield, in addition to the ERA5 data, the power curve of the reference wind turbine is required

Figure 16: Visualisation of the solver and the contained scripts as well as the flow of information within the solver

5.4 Post-Processor

The post-processor prepares the results from the solver in a format, which enables and simplifies their interpretation in order to conduct a comprehensive preliminary site assessment. The preparation of the results shall be done for both the target region and single sites/grid cells. In contrast to the pre-processor and the solver, the post-processor is executed manually, as the visualisation has to be customised to the results. This is especially required, when different regions are compared with each other.

For the visualisation of the results of the target region, a GIS tool is required to correctly assign the data to the corresponding spatial locations. In this work, the MATLAB compatible toolbox "M_Map" is used [52]. It was developed by Prof. Rich Pawlowicz from the *Department of Earth, Ocean and Atmospheric Sciences* of the *Faculty of Science* of *The University of British Columbia*. This software allows to prepare data with spatial reference (longitude and latitude) in different global projections. For this work, the Universal Transverse Mercator (UTM) projection is chosen due to its suitability for presentation of "high-quality maps of small regions of the globe" [53]. Basis for the application of this projection is the WGS 84 reference system. UTM zones are automatically applied based on the regarded location by *M_Map*. Coastline data for the pictures is obtained in high resolution from NOAA [54].

For the visualisation of the results of the basic and advanced criteria for single sites/grid cells, figures, diagrams and functions are created with *MATLAB* scripts and *Microsoft Excel* tools. The information for those single sites/ grid cells is also provided in tabular form.

6 Case Study

In the following chapter, the proposed methodology for a preliminary site assessment is applied to three example sites. This case study shows the methodology and the corresponding procedures. The results are discussed exemplarily to show how they could be applied to a realistic use case. However, a comprehensive content-related interpretation of the results is out of the scope of this work and is therefore not conducted.

Also, the suitability of the developed methodology will be discussed, based on the results. The methodology's strengths and weaknesses are shown. In this chapter, this validation of the methodology is only touched. It will be discussed and summarised in chapter 7.2 *Outlook*.

The chapter is structured as follows; in a first step, the example sites, for which the methodology is conducted, are determined. The second step is the application of the methodology. Here, main components for the application are presented as well as key framework data. In the last step, the results are presented and discussed exemplarily. During this presentation, one of the main advantages of the methodology, the comparability of different sites, is shown as well.

6.1 Example Sites

The selection of the sites is based on different criteria. To show the extent of the methodology, two types of sites are regarded. Firstly, a singular *target region* is chosen. For all target regions, the basic criteria of the methodology are assessed. Secondly, within each region, one *single site* is selected. For these single sites, both basic and advanced criteria are evaluated.

Regions with an obvious reference to offshore wind were chosen. The wind industry in these regions was determined to be at different stages. Therefore, the goal was determined to include one target region, which is already well-explored by the offshore wind industry. One additional target region shall be included with planned and funded offshore wind projects, which are going to be constructed and commissioned within the next years. The third target region was determined to be a high potential site, which is well-regarded by the wind industry but without or with few currently operating projects or projects under construction. For each target region, the single site was selected based on a real and representative offshore wind project. In addition to the state of the industry, it was aimed to include areas from different continents to show this methodology's global applicability.

The selected target regions and single sites are:

- **Proven Area:** Target region *North Sea around the German Bight* and single site based on the operational wind farm *Offshore Windpark "Sandbank"*
- **Planned Area:** Target region *US East Coast around the south of Massachusetts* and single site based on soon-to-be-constructed wind farm *"Vineyard 1"*
- **Potential area:** Target region *South Korea* and single site based on planned *Donghae 1 Floating Wind Farm*

North Sea

The "North Sea around the German Bight" covers the south-eastern bight of the North Sea and is bordered by Denmark and Germany in the east and the Netherlands and Germany in the South. The German Bight itself is German territory.

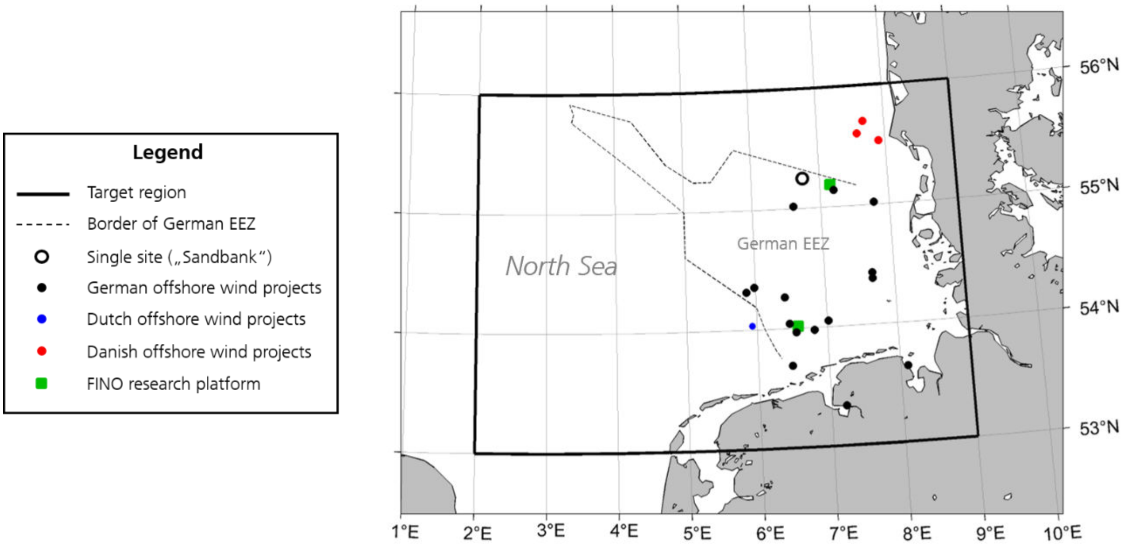


Figure 17: Overview over the target region German Bight (*proven* example site) with a Focus on the German EEZ [52, 55–58]

In the German Bight, the majority of the German offshore wind activities take place. Most of them are located outside of the 12-mile zone within the German Exclusive Economic Zone (EEZ). The first German offshore wind farm, "alpha ventus", was also located within the German North Sea. It was commissioned in 2010 and has a capacity of 60 MW, provided by 12 x 5 MW wind turbines produced by *Areva*, later *Adwen,* and *RePower*, later *Senvion* [59, 60]. In December 2019, there are 17 operating different German offshore wind projects in the German Bight, which add up to a total capacity of almost 4,600 MW [61]. Based on the many different projects which are operated and planned in the North Sea, this area was selected as the *proven* target region within this work. As a single site for more detailed analysis, the location of the German *Offshore Windpark "Sandbank"* was selected. This windfarm was commissioned in 2017 and consists of 72 x 4 MW *Siemens* wind turbines, which add up to a total capacity of 288 MW [58]. In Table 5, an overview over the selected area is provided.

Table 5: Overview over the key characteristics of the selected *proven* example site (North Sea, Offshore Windpark “Sandbank”) for the case study [55–58, 62]

Proven Area	
Target Region	
Area	North Sea (Focus: German Bight)
Coordinates	53°N to 56°N 2°E to 9°E
Size[1]	150.000 km²
Affiliation	Germany Netherlands Denmark United Kingdom
Installed Offshore Wind Capacities	Germany: 4,559.5 MW (17 Projects) Netherlands: 600 MW (1 Project) Denmark: 820.9 MW (5 Projects)
Single Site	
Coordinates	55° 15’ 0”N 6° 45’ 0”E
Affiliation	Germany
Based on Offshore Wind Project	Offshore Windpark „Sandbank“
Status	Operating since 2017
Capacity	288 MW (72 x Siemens SWT-4.0-130)

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[1] For comparison; the size of Germany amounts to 357,578 km²

US East Coast

The US East Coast is a region with high potential for offshore wind in the immediate future. Until now, only few offshore wind projects have been realised despite nearly 2 GW of installed onshore capacity until the end of 2019 [63]. Many states along the US East Coast declare themselves in favour of offshore wind and even announced a wide expansion of offshore wind in the future. In summary, US East Coast states plan for a total installed capacity of 20 GW until 2035 [64]. Among the most ambitious states is the State of New York, whose governor Andrew Cuomo stated that "offshore wind has potential – we know it – the industry is moving that way. We want to locate the industry in this state" [65].

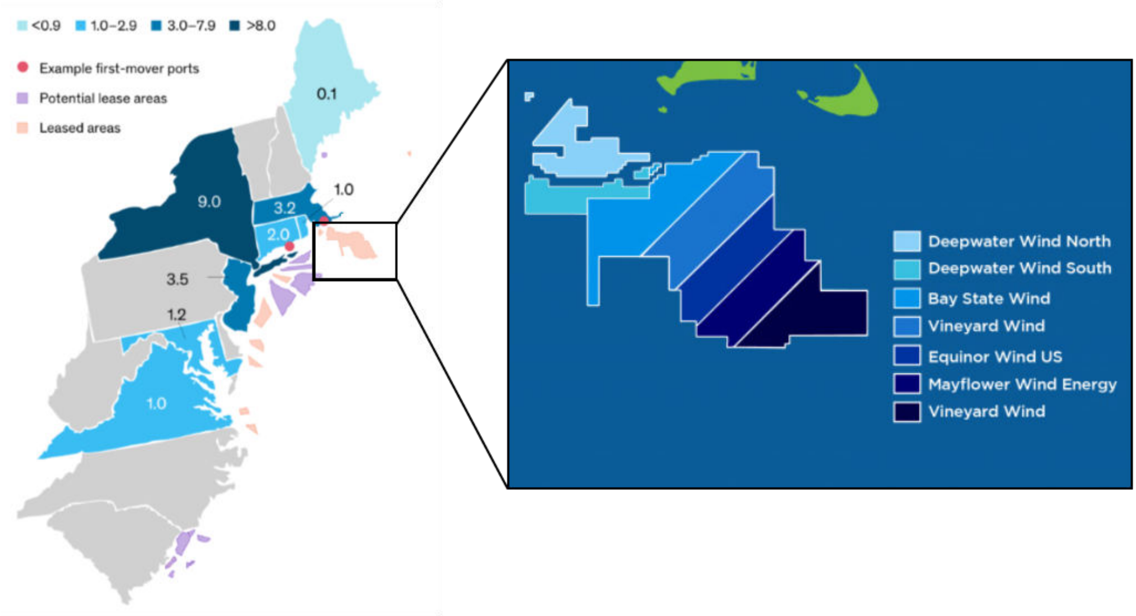

Figure 18: US East Coast states' offshore wind targets until 2035 in GW installed capacity (left, state June 2019) and segmentation of leased area to the south of Massachusetts, USA (right, state April 2019) (based on [64, 66] and modified)

Figure 18 shows the different states along the US East Coast and the announced goals for offshore wind capacities as well as already leased and potential future lease areas (left). On the right, the already leased area between New Shoreham and Martha's Vineyard, close to Long Island, and the corresponding offshore wind projects are presented in further detail. Some of these projects – and many projects along the US East Coast in general – are already at the final planning stage and are going to be constructed soon. An example is the project *Vinyard Wind 1*, which is located in the northern *Vinyard Wind* leasing area. Its construction start was scheduled for 2019. Due to the order from the US Department of Interior for additional analysis regarding the effects on the fishing industry the construction plans are currently being rescheduled [67, 68].

Based on these developments, the US East Coast between New Jersey in the west and Boston in the north (comparable to the area presented in Figure 18 on the right) was selected as target region for the *planned area* of this case study. As single site, the location of *Vineyard Wind 1*, the first wind farm of the *Vinyard Wind* project was chosen. The assigned area for *Vineyard Wind 1* amounts for about 650 km² which approximately corresponds to the size of an ERA5 HRES grid cell at 40°N [69]. The following picture describes the target region and the single site for the US East Coast. The table afterwards summarises the characteristics.

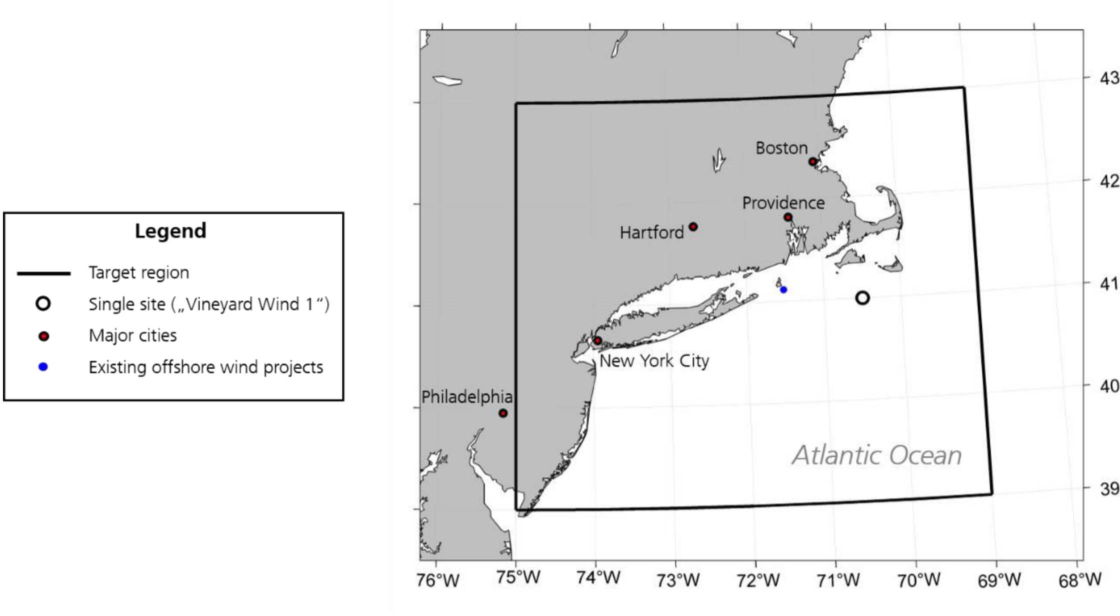

Figure 19: Overview over the target region US East Coast (*planned* example site) with a Focus on the area around New York City [52, 64]

Table 6: Overview over the key characteristics of the selected *planned* example site (US East Coast, Vineyard Wind 1) for the case study [64, 70]

Planned Area	
Target Region	
Area	US East Coast (Focus: Long Island, New York, Massachusetts)
Coordinates	39°N to 43°N 69°W to 75°W
Size	225.000 km²
Affiliation	United States of America
Installed Offshore Wind Capacities	Rhode Island (USA): 30 MW (1 Project)
Single Site	
Coordinates	41° 0′ 0″N 70° 30′ 0″W
Affiliation	Massachusetts (USA)
Based on Offshore Wind Project	Vineyard Wind 1
Status	Start of operations planned 2021
Capacity	798 MW (84 x MHI V164-9.5 MW)

South Korea

The last region, which was selected as *potential area* for the case study, is the country with the least developed wind industry among the selected three: South Korea. In South Korea, two offshore wind farms (total of 64.5 MW) and two demonstrator projects (total of 8 MW) have yet been installed in addition to around 1.3 GW of onshore wind capacity until the end of 2019 [71]. However, according to the *Ørsted*, the wind potential is considerable high: "South Korea is a peninsula surrounded by three seas. We estimate that South Korea's offshore wind power capacity can reach 30 GW." (Park Jung-min, head of the Korean market development at *Ørsted Asia Pacific*) [72] For comparison: This offshore wind potential equals 5 times the installed offshore wind capacity of Germany [73].

In the context of South Korea’s “Renewable Energy 3020 Plan”, South Korea’s Government plans to expand the installed wind capacities (onshore and offshore) to 17.7 GW. Since launching the programme, multiple wind projects have been initiated. The projects, which have been proposed to the Electricity Business Permission (EBP) of the Ministry of Trade, Industry and Energy of South Korea add up to 2,799.8 MW [71].

One highly promoted project is the *Donghae 1 Floating Wind Project*, which was selected as one of the governments R&D projects for the programme “Design of an Offshore Wind Demonstration Complex with 100 MW or more” in 2018 [71]. *Donghae 1* aims for 200 MW of floating wind turbines off the coast of Busan in the south west of South Korea.

The location of Donghae 1 Floating Wind Project is used as a reference for the *single site* location. An overview over the region and its key characteristics are provided in Figure 20 and Table 7.

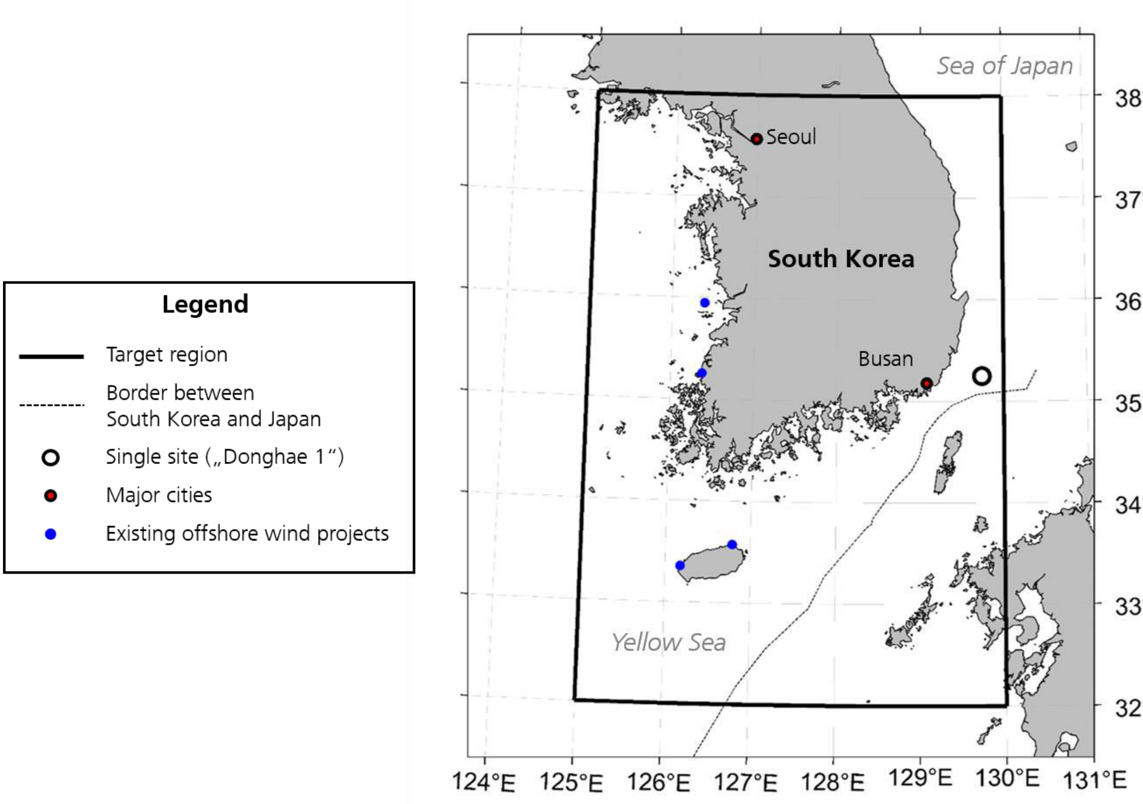

Figure 20: Overview over the target region South Korea (*potential* example site) [52, 71, 74]

Table 7: Overview over the key characteristics of the selected *potential* example site (South Korea, Donghae 1 Floating Wind Project) for the case study [71, 75]

Potential Area	
Target Region	
Area	South Korea
Coordinates	32°N to 38°N 125°E to 130°E
Size	305.000 km²
Affiliation	South Korea
Installed Offshore Wind Capacities	72.5 MW (4 Projects)
Single Site	
Coordinates	35° 15′ 0″N 129° 45′ 0″E
Affiliation	South Korea
Based on Offshore Wind Project	Donghae 1 Floating Wind Project
Status	Start of operations planned 2024
Capacity	200 MW

6.2 Analysis

The site assessment methodology of this work was conducted for the three *target regions* including the *single sites* as specified in the previous chapter. This chapter aims to document the progress of the calculations.

6.2.1 Setup

For the realisation of the site assessment for the three target regions, ERA5 NetCDF-files were obtained via Copernicus CDS API. The downloaded files contained both the spatial area and the temporal period, which is required for the application of the methodology. The files contained the variables specified in *Appendix A – ERA5 Parameters* for the most part.

For the *potential area* South Korea an error occurred during the download. This resulted in the data of the *maximum individual wave height* (“hmax”) not being downloaded for this location. As the case study is conducted to exemplarily show how the methodology works and the individual wave height data was contained for all other regions, it was decided to not repeat the download of the South Korea.

From the borders of the target regions as defined in the previous chapter, the spatial information required as input for the scripts could be derived. For this purpose, all target regions were organised in grid cells. The grid cells are exemplarily presented for the target region *German Bight*. The corresponding figures for the other locations can be found in *Appendix B – Case Study Example Sites*.

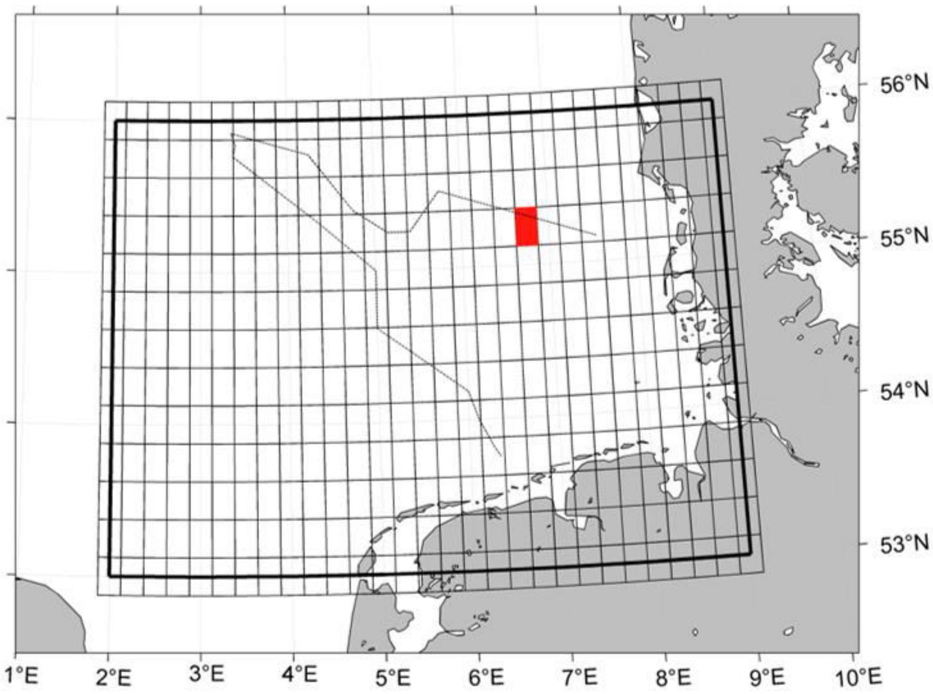

Figure 21: Grid cells for the target region *German Bight* (red = grid cell containing the single site "Sandbank")

The actual spatial information, which is required for the scripts, is formed by a so called "wantedLocations"-file. This MAT-file contains the spatial information of each grid cell and numbers them.

6.2.2 Calculation

In the following table, the information about the calculations are provided.

Table 8: Summary of the key information of the calculations for the case study

	Proven Area North Sea	**Planned Area** US East Coast	**Potential Area** South Korea
Number of Grid Cells	377	425	525
Total Size of ERA5 NetCDF-files	61.9 GB	27.4 GB	22.6 GB
Total Size of ERA5 MAT-files	15.6 GB	14.2 GB	16.5 GB
Total Size of MAT Result files	14.3 GB	11.7 GB	15.1 GB
CPU used	Intel(R) Core(TM) i7-4600U CPU@ 2.10GHz	Intel(R) Core(TM) i7-3770 CPU @ 3.40GHz	Intel(R) Core(TM) i7-3770 CPU @ 3.40GHz
RAM used	12.0 GB	32.0 GB	32.0 GB
MATLAB Version used	R2012b (8.0.0.783)	R2012b (8.0.0.783)	R2012b (8.0.0.783)
Calculation time Pre-Processor	67:03 h	34:10 h	45:46 h
Calculation time Solver	[-][1]	22:56 h	13:28 h

The key information from the calculations show reasonable data. The total size of the "raw" ERA5 NetCDF-files for the North Sea is higher than for the other regions. The reason for this is that the downloaded ERA5 data covered a larger region with many unused variables. Still, even the ERA5 MAT-files are larger than those of the US East Coast. A reason might be that the North Sea data contained almost no land grid cells. As grid cells, which reference sea locations,

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[1] Due to later detected errors, the solver script had to be adjusted and was run multiple times. Therefore, its total calculation time is not available.

contain wave information, the corresponding files are usually larger. This phenomenon applies conversely to the South Korea files.

The processing time seems random. A reason for the little amount of time required for the US East Coast and South Korea is without doubt the high performance hardware, which was used for these calculations. The different times for the processing of these two areas may be reasoned by the remote computer, which was used for the calculation. It may have also been used by other users during the calculations. This, however, cannot be specified retrospectively.

In summary, both space and time required for the application of the methodology cannot be specified or predicted. However, the provided data above shows a range of the data, which can be used as a reference for future planning.

6.3 Results

The developed site assessment methodology has been applied to the example sites in a case study. In this section, the results of this case study are presented. This is done in two steps. Firstly, the results for the three target regions are presented. These results are based on the basic criteria of the methodology; these are compared for entire regions. The results are visualised in maps of the regions. For the preparation of the maps, UTM projection based on WGS 84 is used as described in chapter 5.4 *Post-Processor*. For the colour bars[1] for the results, colour schemes are selected, which clearly express all data of the three example sites. The boundaries of these colour bars do not express any valuation of the data and are selected only for optimal comparison. In this chapter, only a selection of the maps, which were produced during the case study are presented. In order to provide complete information about the results of the case study, the full set of the maps can be found in *Appendix C – Case Study Results*. After the presentation of the results for the target regions, the more comprehensive results for the single sites are presented in a second step. This comprises both the basic and advanced criteria.

The presentation of the results and their discussion serve two purposes: Firstly, it is shown exemplarily, which types of results are produced by this work's site assessment methodology and how they can be used. Therefore, the results for several criteria are interpreted exemplarily regarding offshore wind purposes.

The second purpose of the presentation and discussion of the results is to work out anomalies of the methodology, the post-processor and its visualisation style. This lays the basis for the review of the methodology. The results of the site assessment methodology are compared to publically available data in order to review the quality of the results as well. This comparison is not extended to a comprehensive validation of the results.

6.3.1 Target Regions

In this first part, the results for the target regions are presented. For the presentation, the different basic criteria are consecutively covered for all three target regions.

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[1] Colour bars define the scale for the data and the value coding

Mean Wind Speed

The following maps visualise the mean wind speeds for each grid cell in the target regions.

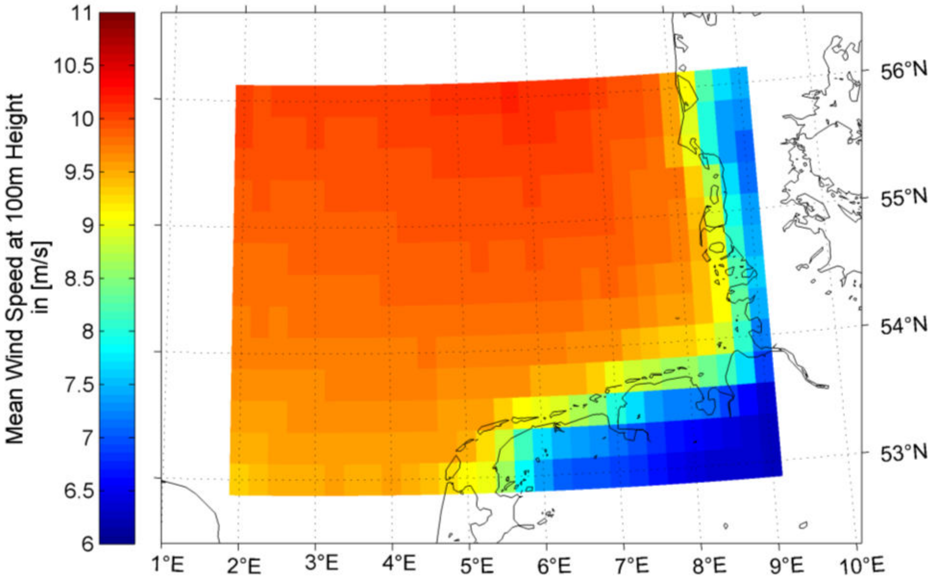

Figure 22: Mean wind speeds at 100 m height in the target region *German Bight*

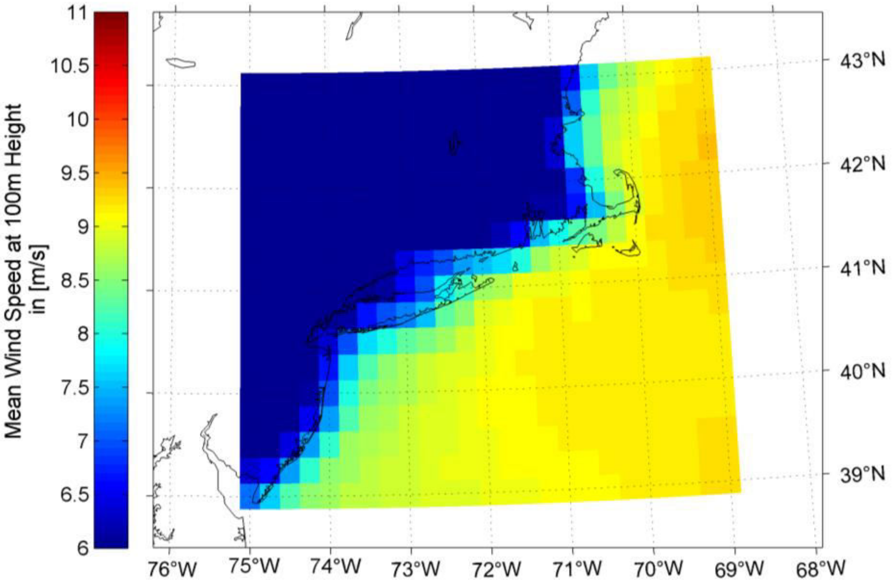

Figure 23: Mean wind speeds at 100 m height in the target region *US East Coast*

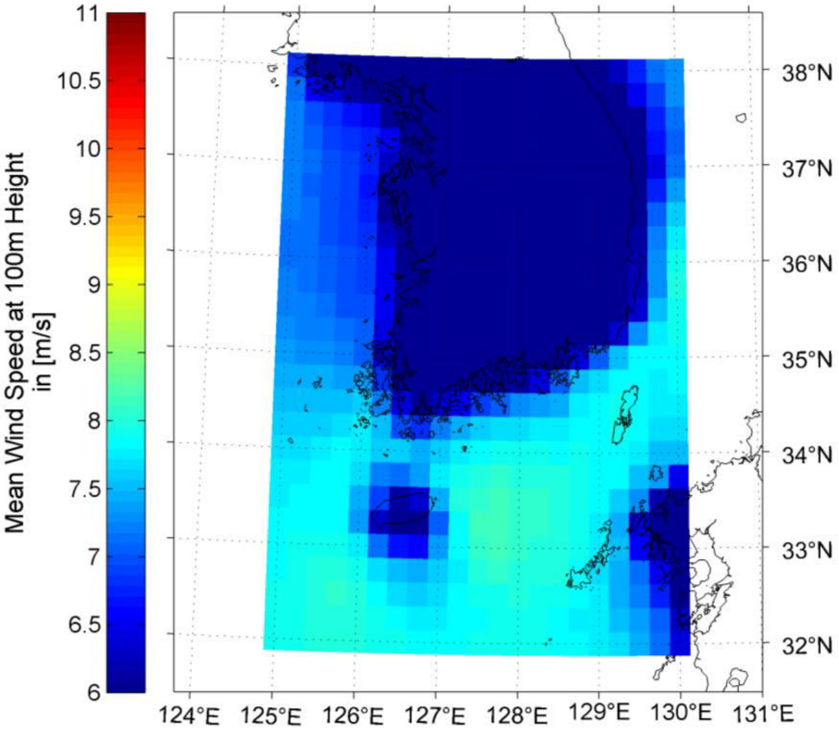

Figure 24: Mean wind speeds at 100 m height in the target region *South Korea*

The graphics show that the average wind speed for offshore location in the German Bight (approx.. 10 m/s) and at the US East Coast (approx. 9 m/s) are considerably higher than in the seas around South Korea (approx.. 7 – 8 m/s). In the German Bight, the mean wind speeds increase towards the north from approximately 9 m/s close to the English Channel and the coastline to above 10 m/s in the open North Sea. For South Korea, it stands out that the mean wind speeds in the south and the east are generally higher than in the northern Yellow Sea. Onshore, the mean wind speeds at both the US East Coast and South Korea fall below 6 m/s, which is not further specified by the scale of the graphics. The mean wind speeds for onshore locations close to the German Bight (German and Dutch coast) are slightly higher. The lower decrease of the wind speeds for onshore locations at the German and Dutch coast in comparison to those at the US East Coast and in South Korea can be explained by the shape of the orography. While the US East Coast is covered by dense woodland and South Korea has mountain ranges along the coasts, the German and Dutch coast area is largely plain, which does not affect the wind speed in a similar way. Another reason may be the main wind directions. In the case of the North Sea, this results in large undisturbed areas, which allow the wind speed to increase.

Expected Annual Energy Production (AEP)

The visualisation of the AEPs based on the 8 MW LEANWIND reference wind turbine largely corresponds to those of the mean wind speeds.

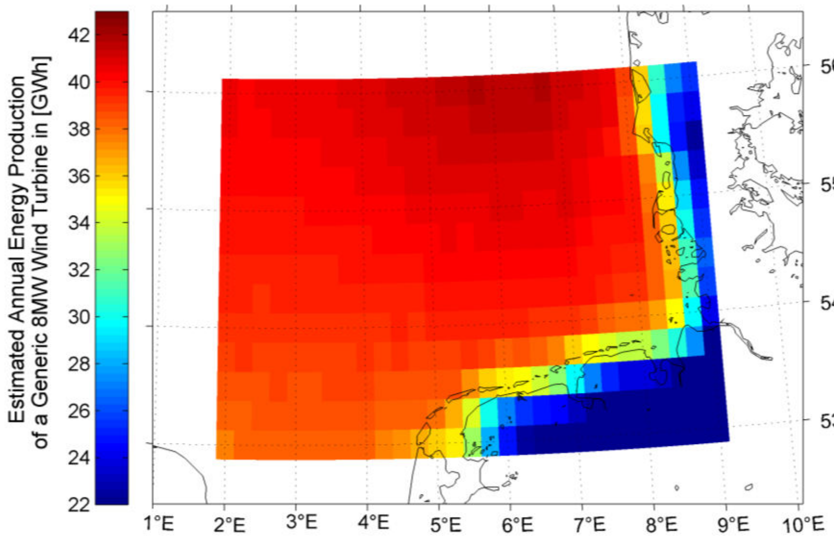

Figure 25: Estimated Annual Energy Productions (AEP) of the LEANWIND 8 MW reference wind turbine in the target region *German Bight* [42]

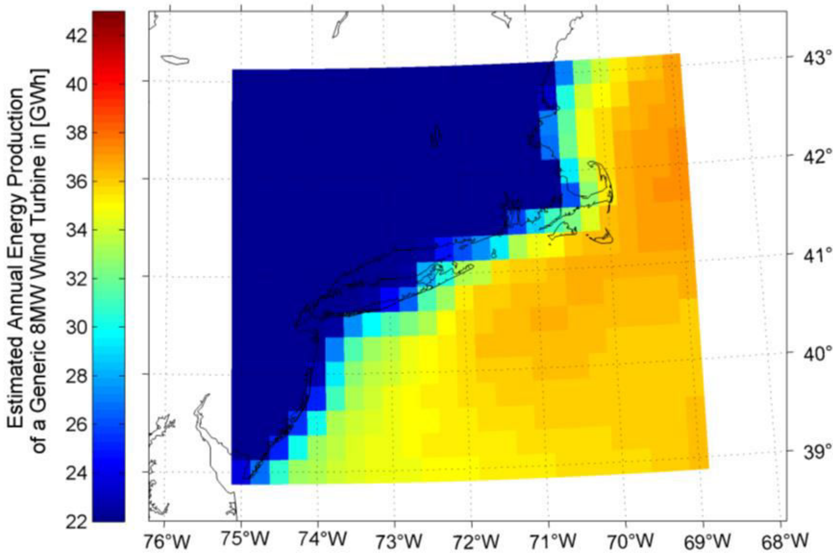

Figure 26: Estimated Annual Energy Productions (AEP) of the LEANWIND 8 MW reference wind turbine in the target region *US East Coast* [42]

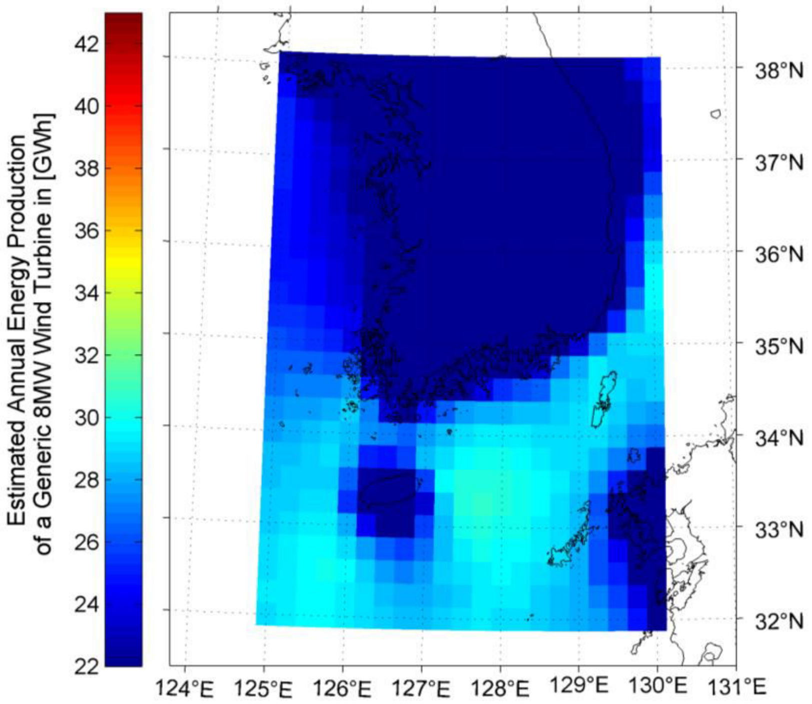

Figure 27: Estimated Annual Energy Productions (AEP) of the LEANWIND 8 MW reference wind turbine in the target region *South Korea* [42]

The results for the estimated AEP are comparable to those of mean wind speeds. However, the differences between the three locations become larger, as the wind speed affects the power production cubically and not linearly. Though the mean wind speed does not represent the entire wind spectrum, the differences in the AEP are usually higher than those in the mean wind speeds. For example, a location in the German Bight with a mean wind speed of 9.5 m/s produces approximately 40 GWh per annum. For a location in South Korea with a mean wind speed of 8 m/s and an AEP of 30GWh, this corresponds to a 19% higher mean wind speed but a 33% higher AEP. Based on the results from the AEP calculation, the German Bight is the most productive region in terms of a large AEP. This applies to the entire German Bight. At the US East Coast, a wind farm in the northeastern region would result in a marginally higher AEP. For South Korea, the northern parts of the Yellow Sea provide roughly 15% lower wind resources than in the southern and eastern seas around the mainland. In combination with the lower mean wind speed in South Korea, different wind turbines should be considered. These wind turbines should operate at full load at lower wind speeds.

Extreme 10-min average wind speed with different recurrence periods

The following section covers the extreme wind speeds with different recurrence periods. Firstly, the results for the wind speeds with a recurrence period of 1 year are presented.

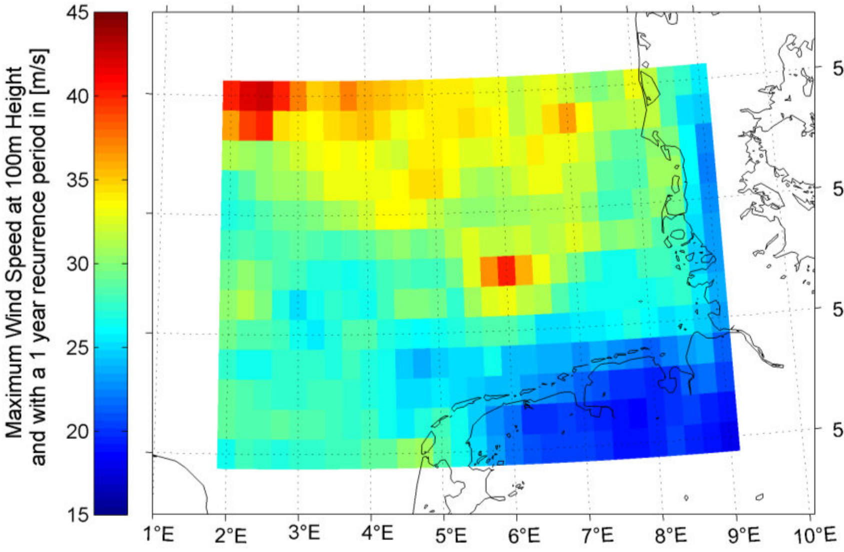

Figure 28: Extreme 10-min average wind speeds with a 1-year recurrence period in the target region *German Bight*

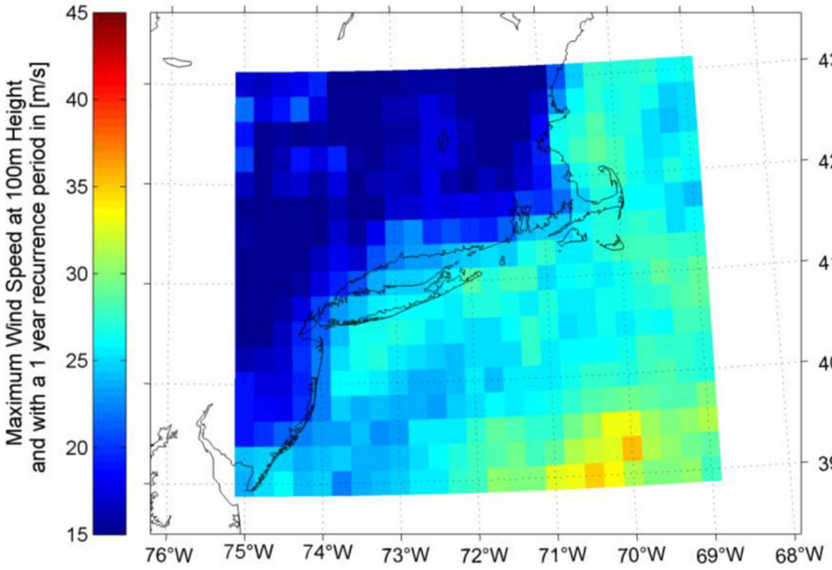

Figure 29: Extreme 10-min average wind speeds with a 1-year recurrence period in the target region *US East Coast*

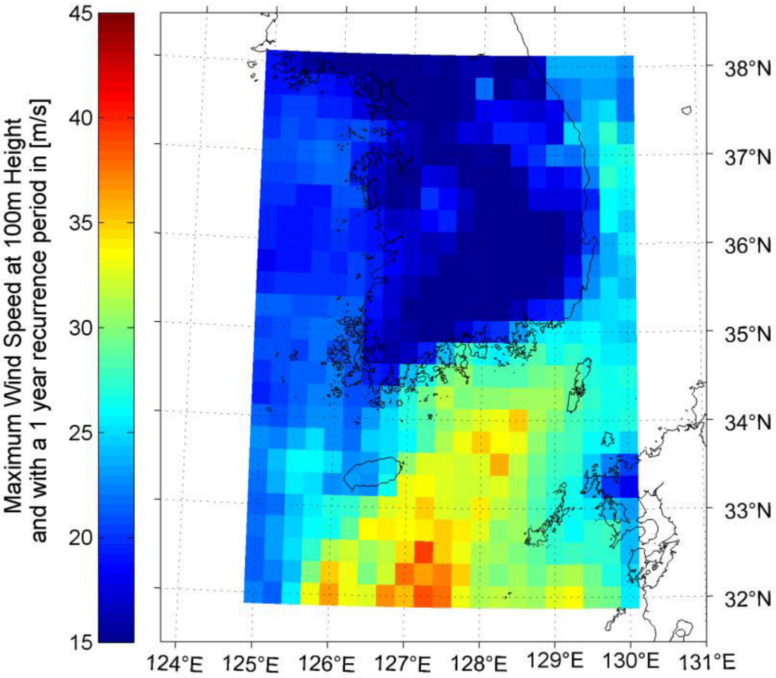

Figure 30: Extreme 10-min average wind speeds with a 1-year recurrence period in the target region *South Korea*

The maps containing extreme 10-min average wind speeds with a recurrence period of one year show comparable values for the German Bight and South Korea. Though the mean wind speeds in the German Bight are considerably higher, this does not apply to the one-year extreme winds. While both regions show one-year extreme values of about 25 m/s in coastal regions, in the north western parts of the German Bight and in the sea to the south of South Korea in the direction of the East China Sea, one-year extreme winds of 35 m/s are predicted. There are single grid cells with even higher extreme wind speeds in both reviewed regions. In South Korea, these wind speeds are slightly lower than 40 m/s, while in the German Bight even wind speeds of 43 m/s are predicted for single locations. Taking into account the lower mean wind speeds for South Korea, this means that the wind speeds in this region have a higher variance. For the German Bight, many wind farms are planned and operating within these regions with high extreme wind speeds. In South Korea, wind farm projects concentrate on locations with lower extreme winds, for example along the South Korean west coast.

For the US East Coast, the annual extreme wind speeds are generally lower compared to the North Sea or South Korea. Despite the grid cells in the far southeastern corner in the direction of the open sea, those wind speeds are predicted to be below 28 m/s. This also applies for the locations with much higher AEP than for example the South Korean locations. Even though a higher AEP is predicted, the extreme wind loads are predicted to be much smaller. Upon applying different scales for the extreme wind speeds with a 50-year recurrence period, the results seem similar for both the 1-year and the 50-years recurrence periods. However, for certain extreme events, like for example hurricanes, additional correction factors may be required as found out by C. Qiao et al. [76]. The reason reanalysis models often underestimate these unusual events. This correction may change the extreme wind estimation.

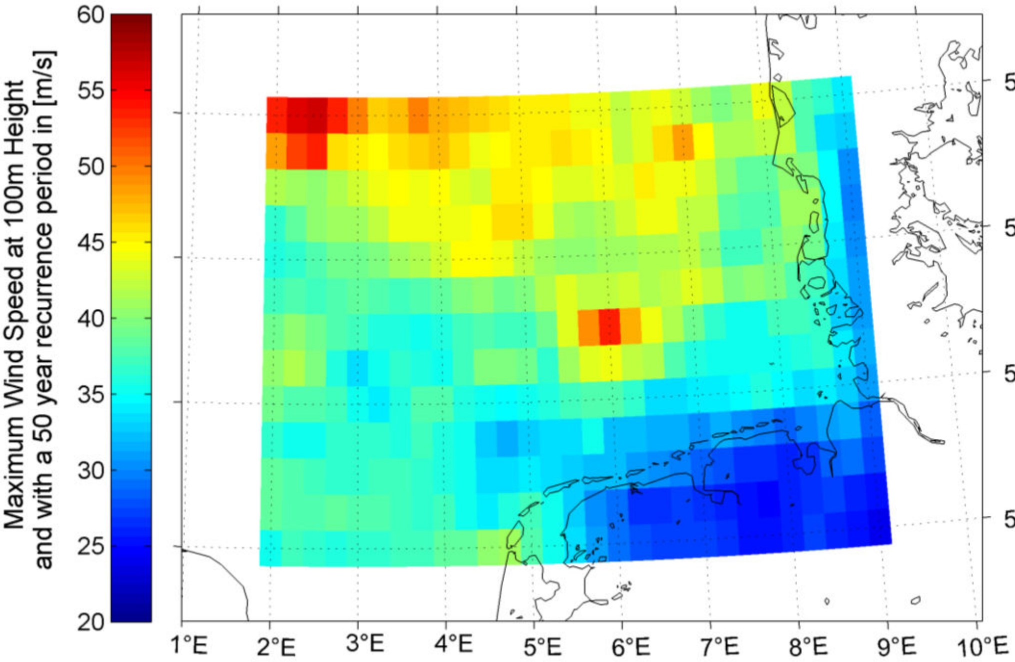

Figure 31: Extreme 10-min average wind speeds with a 50-year recurrence period in the target region *German Bight*

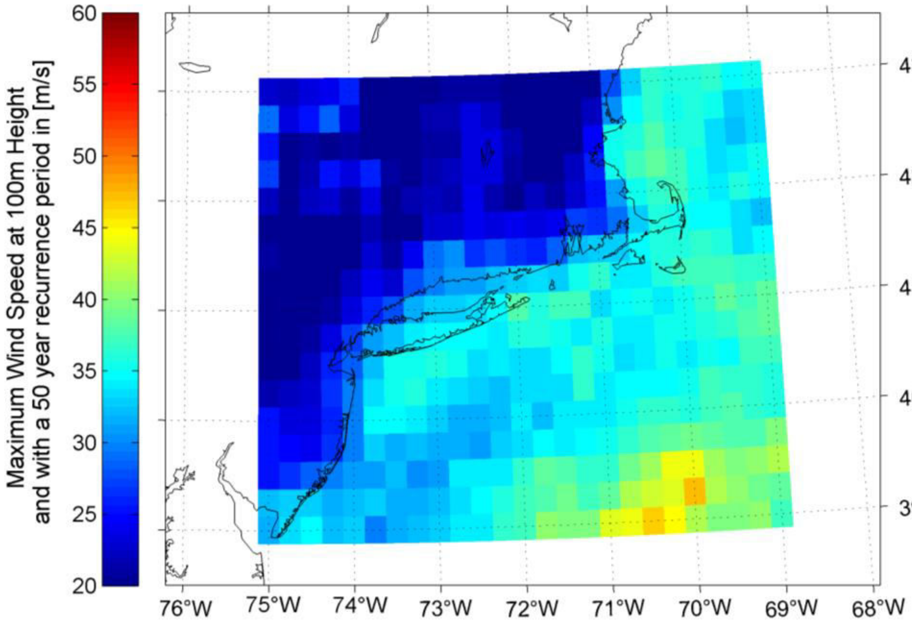

Figure 32: Extreme 10-min average wind speeds with a 50-year recurrence period in the target region *US East Coast*

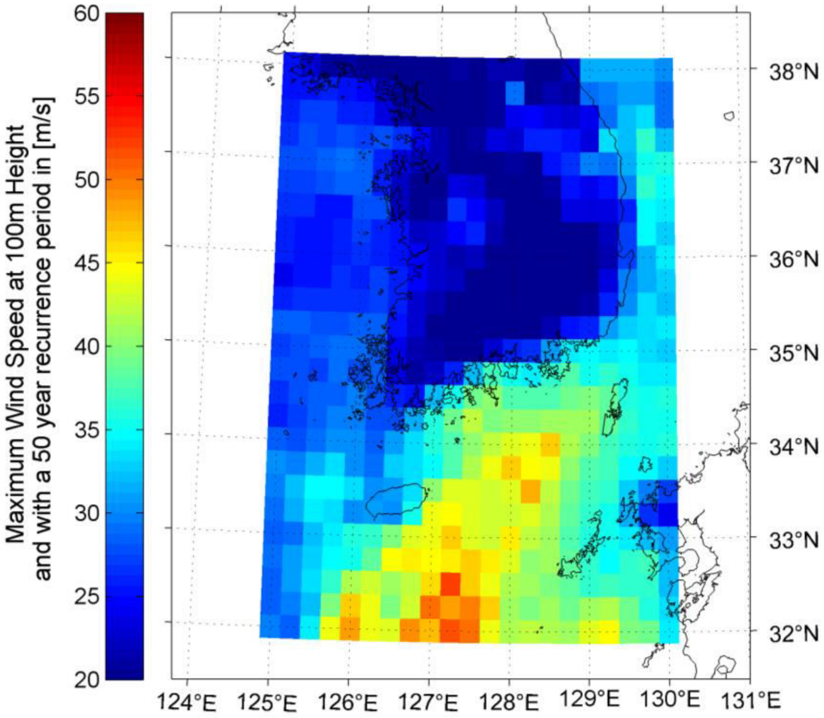

Figure 33: Extreme 10-min average wind speeds with a 50-year recurrence period in the target region *South Korea*

For locations with high extreme one-year wind speeds, the results also show high 50-year extreme wind speeds. However, the absolute values for these estimated extreme values are obviously higher. While for the target region at the US East Coast, 50-year extreme wind speeds of 35 m/s are common, for the southern parts of the reviewed target region South Korea and for the northwestern part of the German Bight, 50-years extreme winds around 45 m/s are common. This furthermore underlines the findings from above: For locations at the US East Coast, high AEPs are estimated while also predicting comparably low extreme wind speeds and corresponding loads. Therefore, wind turbines for these locations do not need to be designed for extremely severe wind conditions.

Regarding the extreme wind speeds for the German Bight, extremely high wind speeds are calculated for several grid cells. An example is the grid cell at 54.5°N and 6°E. Here, 50-year extreme wind speeds of well over 50 m/s are predicted. The adjacent grid cells to the north and south contain much lower values. The explanation for this outlier is not clear, as no geographical particularities are apparent and the calculation of the extreme wind speed has been conducted correctly. The question arises, whether this location is simply more vulnerable to high extreme wind speeds or whether the high values are based on anomalies in the ERA5 wind model. The validation of the ERA5 data is not conducted within this work, therefore, the former has to be assumed. For offshore wind siting, this means, that a wind farm location should be found outside of this area to avoid the much higher wind loads.

Extreme wave heights with different recurrence periods

In this part, the results for both extreme individual and extreme significant wave heights with both 1-year and 50-year recurrence periods are covered. In order to only exemplarily show the results, not all of these four criteria will be presented and discussed for each target region. To be able to compare the individual and the significant wave height more precisely, similar scales are applied in this section. This may result in the significant wave heights appearing less severe. For a comparison of sites within a single region or for the interpretation of only significant or individual wave height, the scales should be adjusted. An example map with a scale, which is applied based on the results of the region alone, is presented for the German Bight and the extreme significant wave height with a 1-year recurrence period in Figure 34. The same results are presented in Figure 35 with a combined scale for individual and significant wave heights and discussed afterwards.

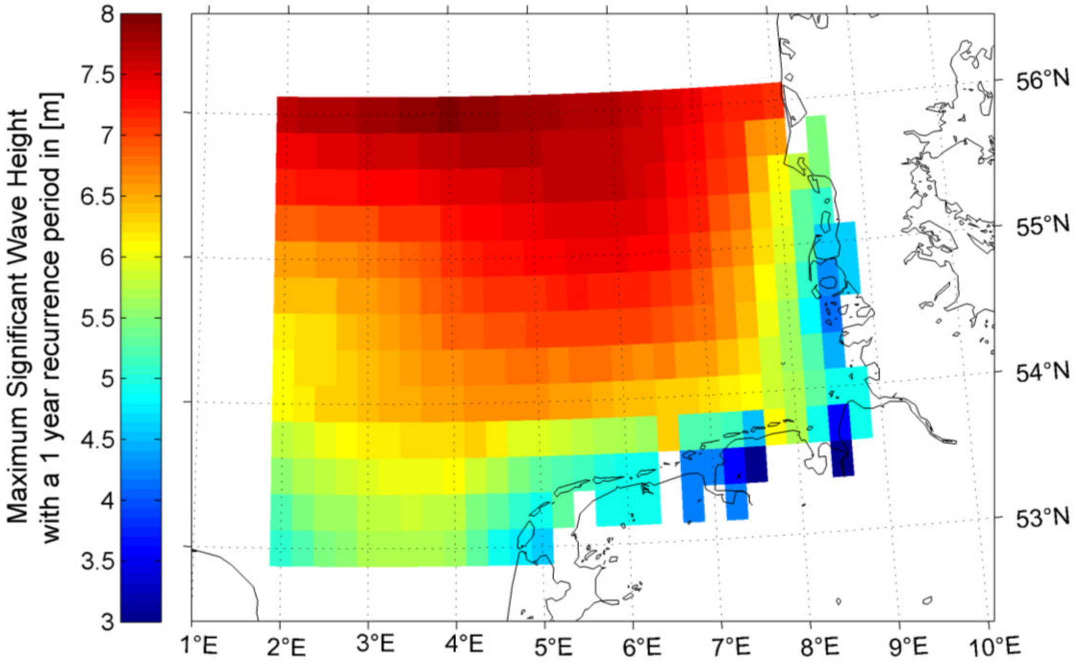

Figure 34: Extreme significant wave heights with a recurrence period of 1 year in the target region *German Bight* with an individual scale

For the comparison, the extreme significant wave heights with a 1-year recurrence period are presented for all three target regions.

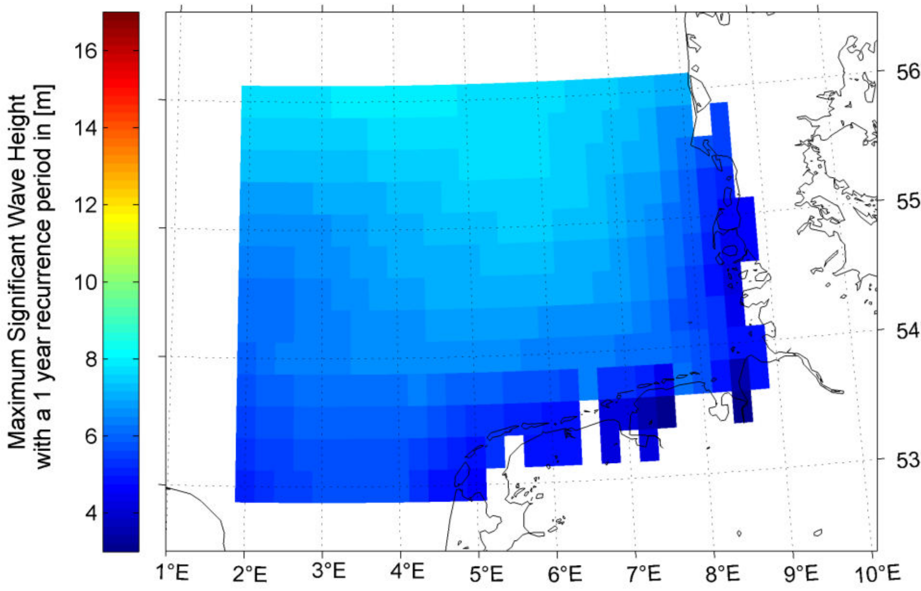

Figure 35: Extreme significant wave heights with a recurrence period of 1 year in the target region *German Bight*

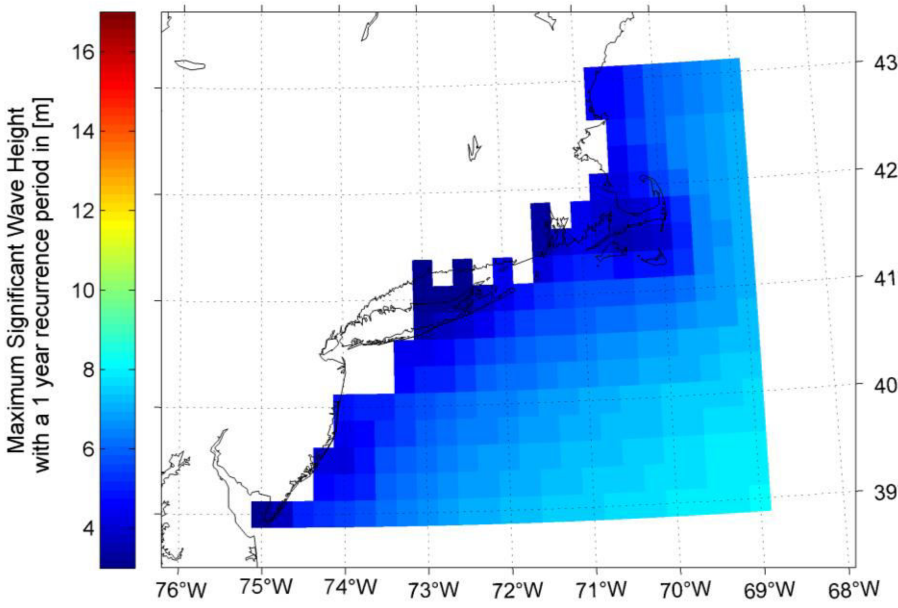

Figure 36: Extreme significant wave heights with a recurrence period of 1 year in the target region *US East Coast*

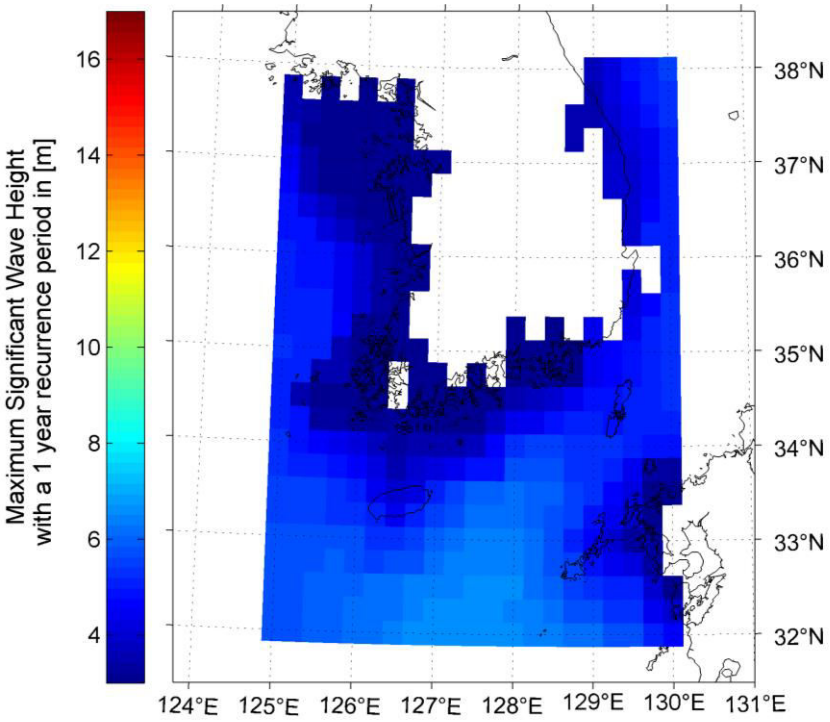

Figure 37: Extreme significant wave heights with a recurrence period of 1 year in the target region *South Korea*

It is obvious that the coverage of the wave data does not seem very accurate compared to the coastline. Along the coasts, grid cells are located entirely onshore and even though contain wave data information. Examples are the grid cells in the German Bight at 53.5°N and 7.5°E or in South Korea at 37.5°N and 129.75°E. In contrast, there are also grid cells located entirely offshore, which do not contain wave data, like at the US East Coast at 40.25°N and 73.5°W or in South Korea at 35.75°N and 129.75°E. There is no constant bias, like a lateral shift into one direction. This eliminates the possibility of an error in the spatial referencing within the methodology. The ECMWF was contacted regarding this anomaly. According to ECMWF experts, the reason for the inconsistent coverage is the resolution of the ocean data being lower than the resolution of the atmospheric data. Due to multiple interpolation steps during the storing of the data on the CDS and the data download, the wave data may be overwritten inaccurately for single locations [77]. This has to be kept in mind when interpreting the wave results.

The extreme wave heights with a recurrence period of 1 year increase with the distance to the coast. Close to the shore, these extreme 1-year wave heights are around 4 m for all three locations. The reason is that the more shallow coastal water only allows for smaller wave heights. The lower wind speeds close to the shore also contribute to that. For the German Bight and the US East Coast, the 1-year significant wave heights constantly increase with further distance to shore to about 8 m for the most distant grid cells. In South Korea, generally lower wave heights are predicted. An explanation for this are the numerous islands around South Korea in contrast to the open seas to the east of the US East Coast and the north-west of the German Bight.

The graphics of the individual wave heights with a 1-year recurrence period show a similar picture despite containing higher absolute values for the wave heights. This is shown exemplarily for the German Bight in the following figure.

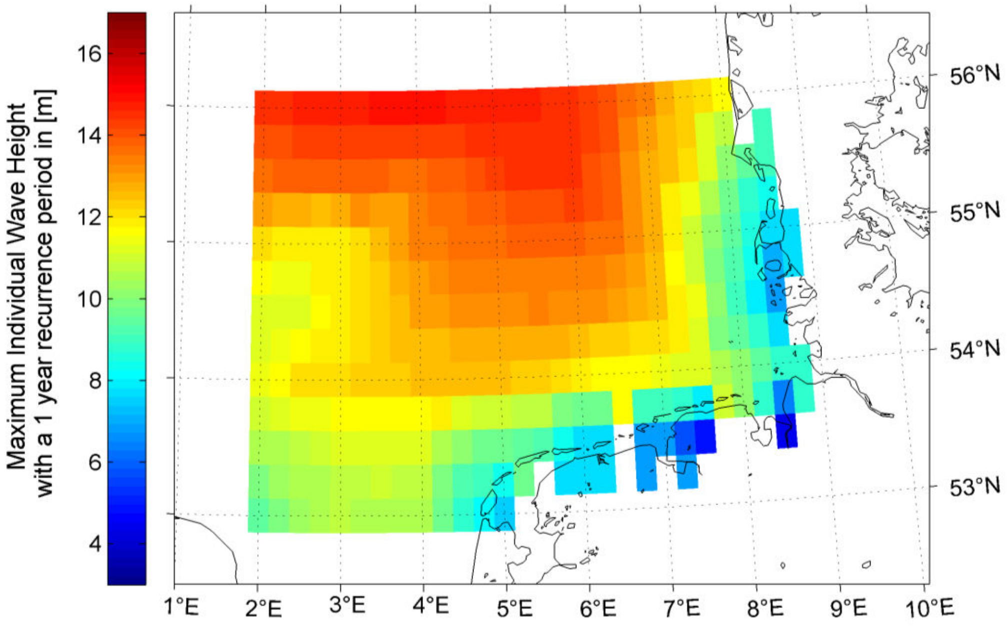

Figure 38: Extreme individual wave heights with a recurrence period of 1 year in the target region *German Bight*

Regarding the extreme wave height in the German Bight, single waves with heights exceeding 10 m have to be considered for almost all locations. Further away from the shore, heights of approximately 15 m are predicted.

For the wave heights with a 50-year recurrence period, the proportional correlation with the distance to shore does not necessarily apply. For the German Bight the following results are produced by the site assessment methodology.

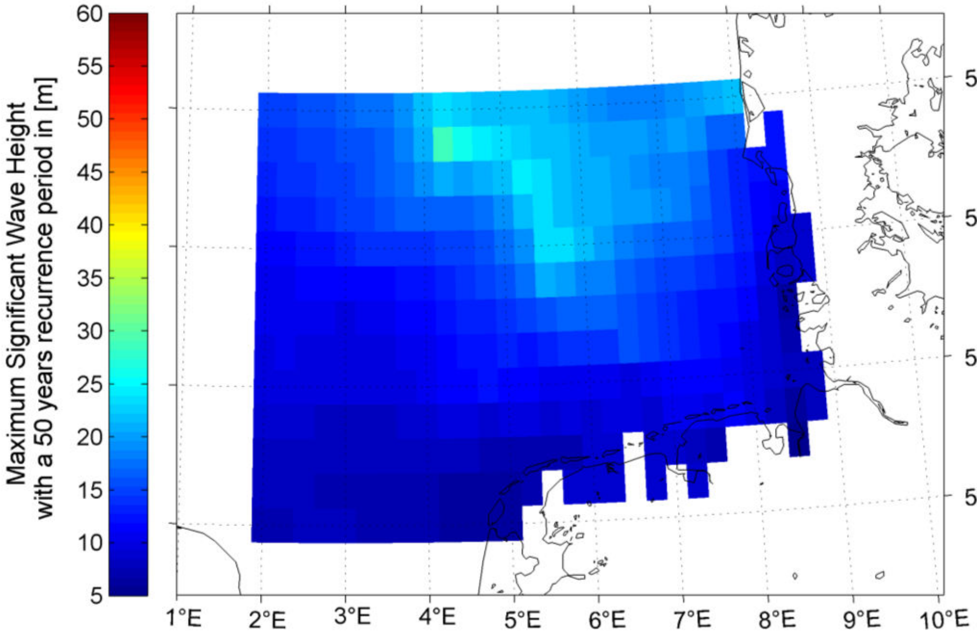

Figure 39: Extreme significant wave heights with a recurrence period of 50 years in the target region *German Bight*

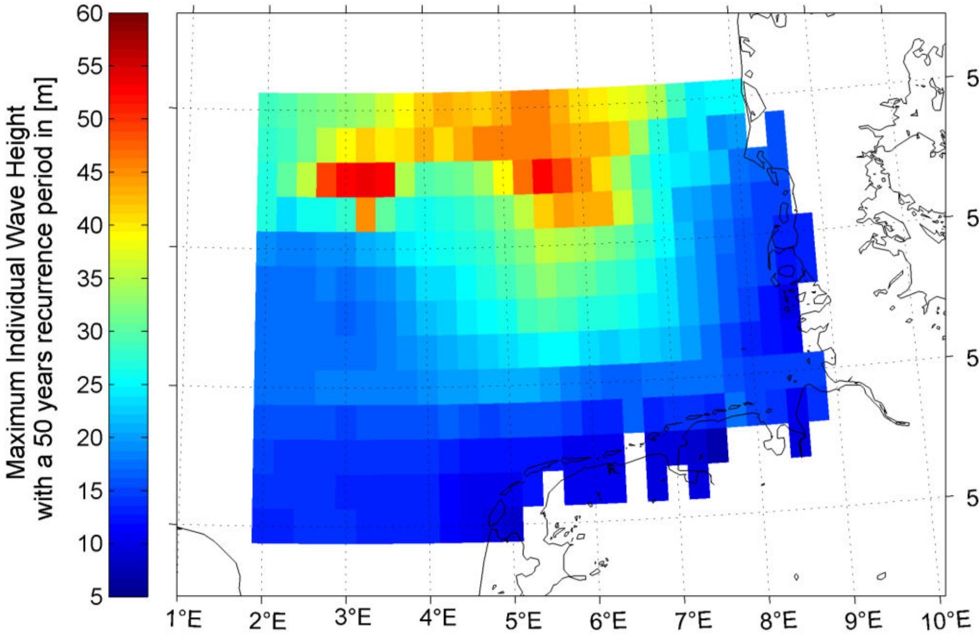

Figure 40: Extreme individual wave heights with a recurrence period of 50 years in the target region *German Bight*

For the 50-year extreme significant wave heights, the height of the waves is correlated to the distance to shore. The highest waves in the North Sea are predicted beween the United Kingdom (to the west of the maps boundaries) and Denmark in the east. Maximum significant wave heights of up to 30 m are predicted. In the area of the German EEZ, the predicted wave heights are consistently lower than 25 m. The locations of the maxima of the predicted 50-year extreme individual wave heights do not correspond to those of the significant wave heights. There are grid cells without especially high significant wave heights but with very high individual wave heights, like the grid cell at 55.5°N and 3.25°E, where individual wave heights of up to 53 m are predicted.

A reason for this may be found in the results of the site's bathymetry. As shown later in Figure 48, the water depth is reduced significantly from 70-100 m to only 20-30 m towards the grid cell with the highest predicted individual wave height. As K. Trulsen et al. showed, such a bathymetry change can increase the probability of high extreme waves [78]. Based on this prediction, the location is not well suited for offshore wind applications. For the regions, which are closer to the Danish-German shore or towards the English Channel, considerably lower extreme waves are predicted, which can be included in the design basis more easily. Another reason for the extremely high numbers might be an error in either the implementation of the extreme value calculation or the ERA5 extreme wave statistics. None of the possibilities could be confirmed or refuted within the scope of this work.

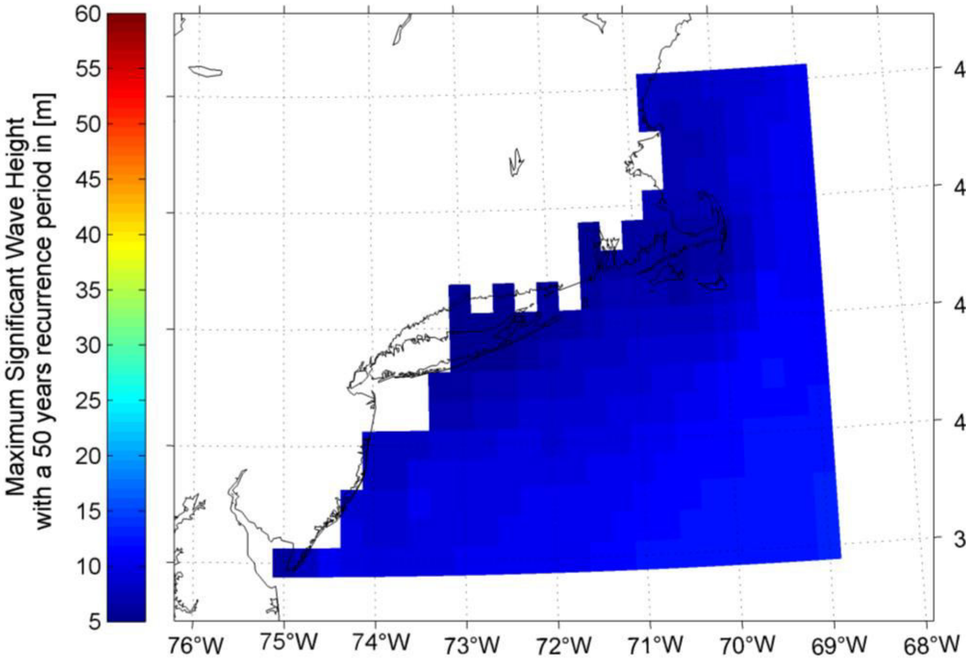

Figure 41: Extreme significant wave heights with a recurrence period of 50 years in the target region *US East Coast*

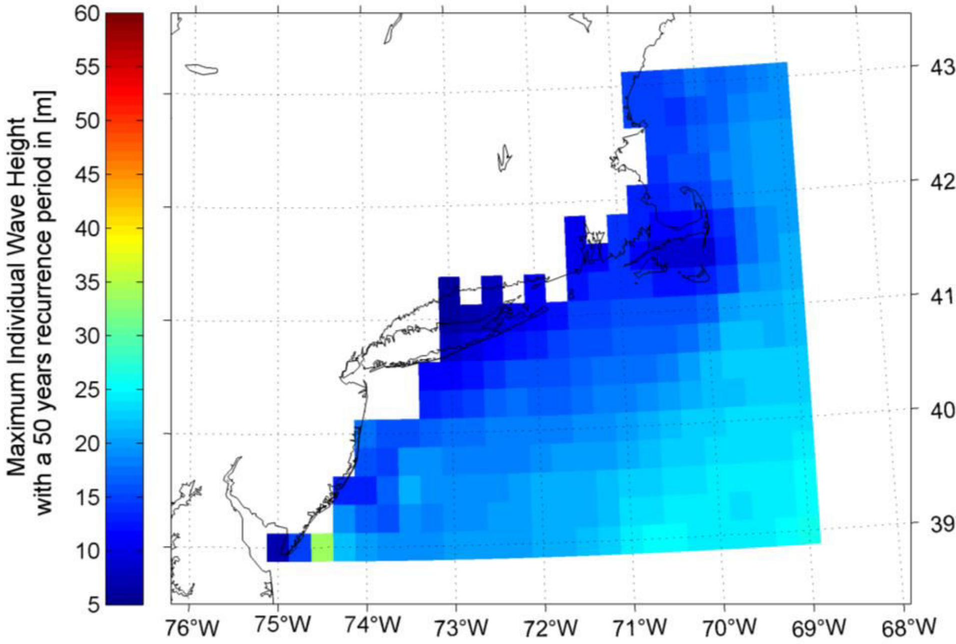

Figure 42: Extreme individual wave heights with a recurrence period of 50 years in the target region *US East Coast*

The extreme significant wave heights at the US East Coast are considerably lower than in the German Bight. Though the heights of the waves for the two regions are comparable for coastal regions, the maxima, which are located far from shore, are very different. The 50-year values for the significant wave height at the US East Coast does not exceed 15 m, even for grid cells far from the shore. This corresponds to other publically available data for the East Coast region. For example, EU Horizon2020 project “LIFES50plus”, which researched the state of the art of floating wind, assumed a 50-year significant wave height of 10.9 m for the Gulf of Maine, which is located to the north of the target region [79].

For the individual wave height, maximum wave heights of 25 m are predicted. The only exception is the grid cell at 39°N and 74.5°W, where a 50-year extreme individual wave height of approximately 33 m is predicted. The predictions for individual wave heights around this grid cell are much lower in the range of 10-23 m. For this grid cell, higher individual wave heights are predicted throughout the entire time series. For offshore wind siting, this location has therefore to be handled carefully. More detailed analysis is suggested in order to derive the reason for the comparably high waves.

For the target region *South Korea*, only the significant wave heights are available as mentioned in chapter 6.2.1 *Setup*.

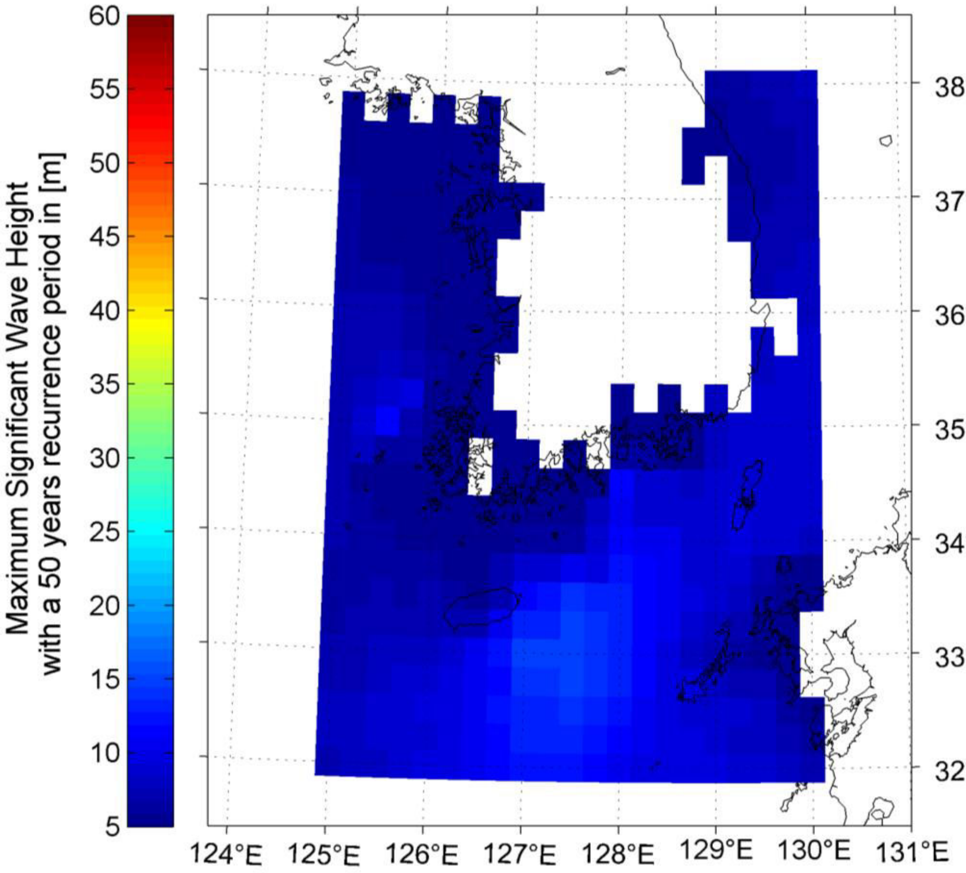

Figure 43: Extreme significant wave heights with a recurrence period of 50 years in the target region *South Korea*

The 50-year extreme significant wave heights in the target region South Korea are even lower than at the US East Coast. For the entire region, the highest predicted significant wave height is approximately 20 m. For the grid cells at the west and east coast of the mainland, the predicted wave heights are approximately 10 m. This especially suits hydrodynamical sensitive offshore wind concepts, like floating wind. These concepts are vulnerable to waves and the comparably low wave heights, even with long recurrence periods would facilitate the design.

Accessibility

In the methodology of this work, the accessibility for different sites is determined as well. The accessibility determines the relative amount of the time, where the wave height does not exceed the limitation for a period equal or longer than the time window. In detailed analyses, the accessibility is often reviewed for different seasons of the year, as the accessibility may vary for different months.

The results of the assessment of the accessibility show, that there are only minor differences for different weather windows. For all three target regions, the accessibility only changes by single percentage points for a larger weather window. This is shown in the following two graphics of the accessibility in the target region German Bight.

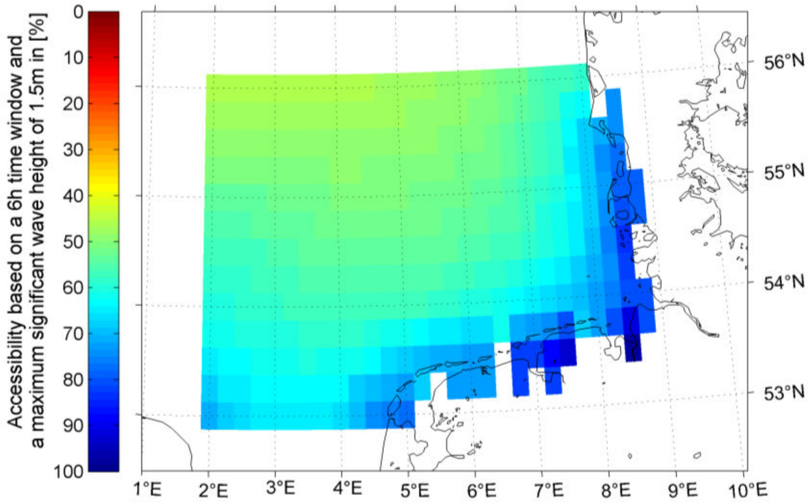

Figure 44: Accessibilities based on a 6 h weather window (Hs≤1.5 m) in the target region *German Bight*

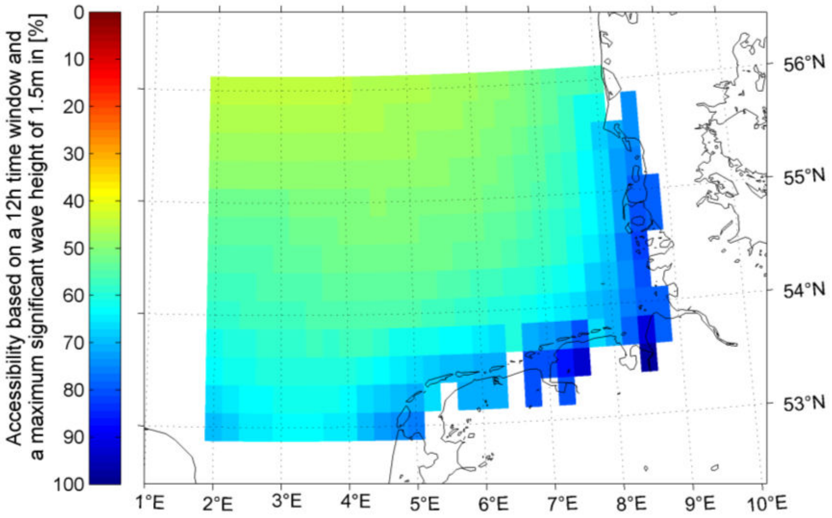

Figure 45: Accessibilities based on a 12 h weather window (Hs≤1.5 m) in the target region *German Bight*

Due to the minor differences between the different weather windows, the graphics with the accessibilities for the target regions US East Coast and South Korea are only presented for the 12 h weather window.

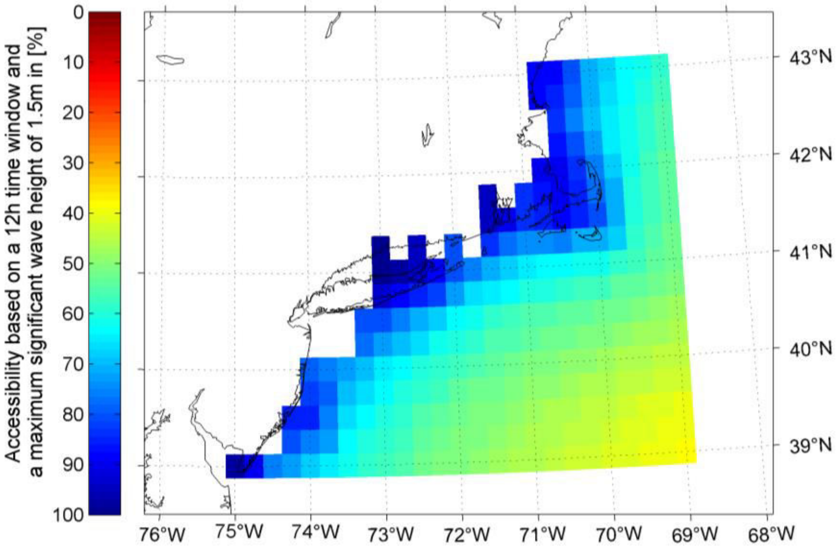

Figure 46: Accessibilities based on a 12 h weather window (Hs≤1.5 m) in the target region *US East Coast*

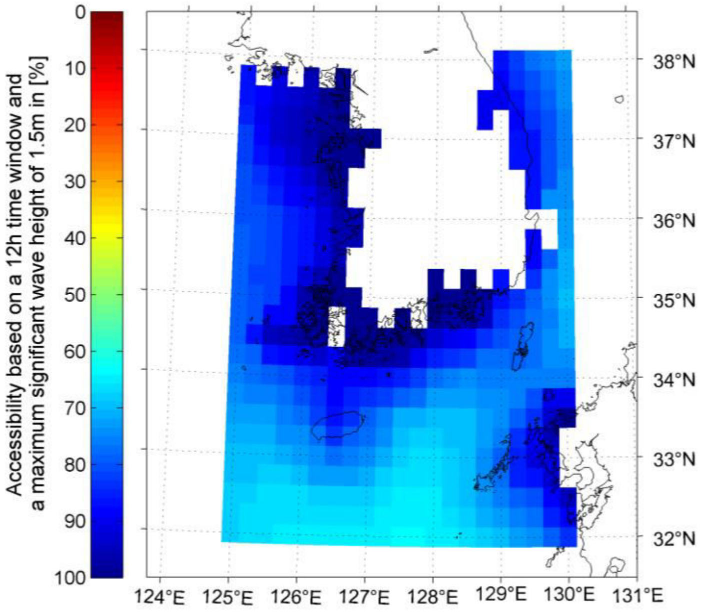

Figure 47: Accessibilities based on a 12 h weather window (Hs≤1.5 m) in the target region *South Korea*

The reviewed region at the US East Coast has the largest area with the low accessibility among the three regions. In the southeast, there are grid cells with accessibilities below 40%. This is comprehensible, as this area is directed more towards the ocean. However, in this area, no wind farms are planned. In the areas of the US East Coast closer to the shore, where actual wind farms are planned and constructed, high accessibilities of over 60% are predicted. In the German Bight, comparable values can be found. For grid cells within 50 km to the shore, the accessibility is higher than 60% as well. Within the German EEZ the results show accessibilities of approximately 50%. South Korea has the highest accessibility with 80-90% at the west coast and between the mainland and the large island Jeju to the south. In the east and further to the south, this accessibility decreases to about 60-70%. Still, this is a much higher accessibility rate than for the other regions. The accessibility is especially important for installation processes and marine operations in general. For South Korea, these operations seem therefore favourable.

Bathymetry

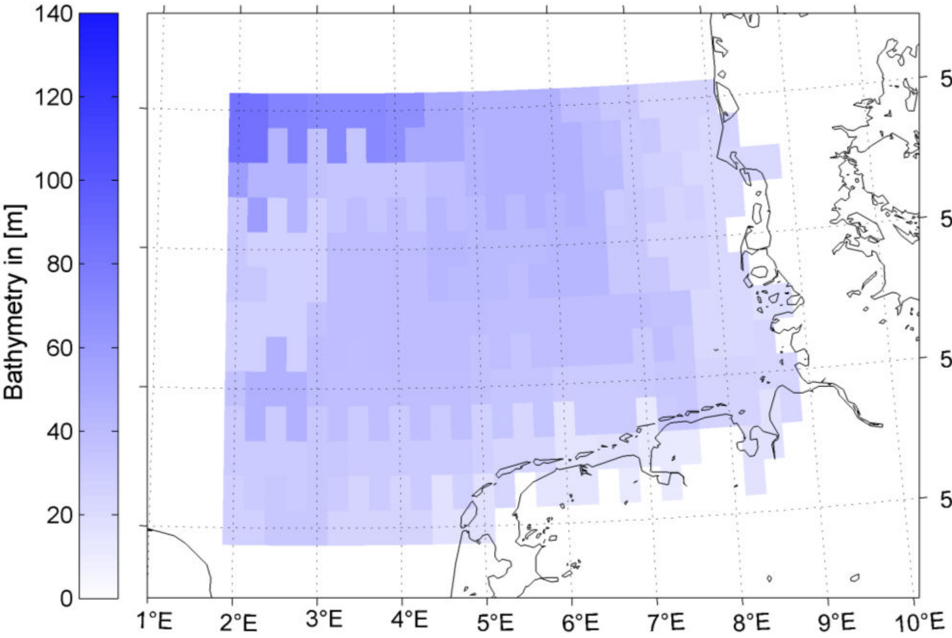

Figure 48: Bathymetry in the target region *German Bight*

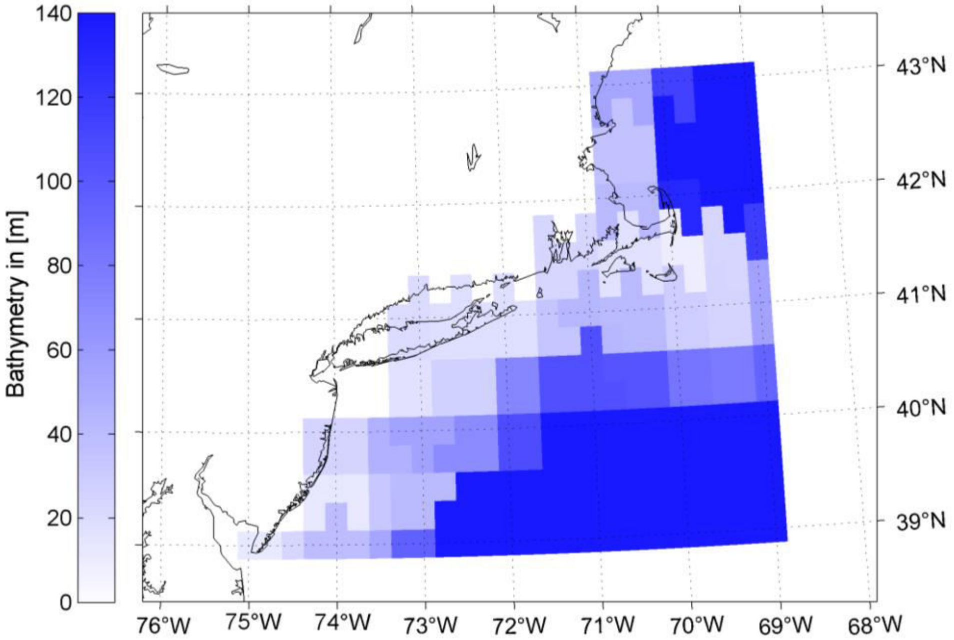

Figure 49: Bathymetry in the target region *US East Coast*

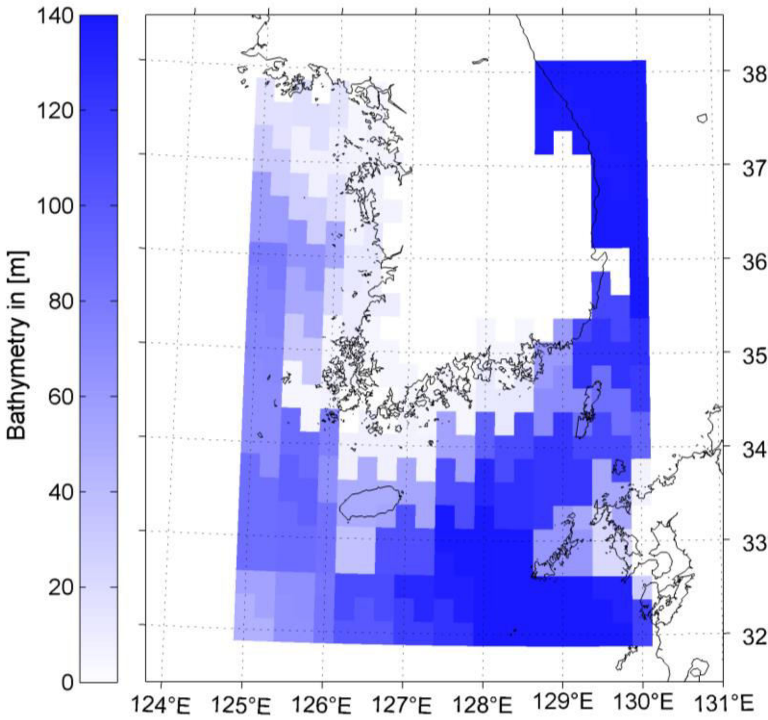

Figure 50: Bathymetry in the target region *South Korea*

The results of the assessment of the bathymetry for the three target regions show an even more inaccurate assignment of water depths to offshore locations. The effect for the bathymetry data is even more distinct than for the wave data, as even larger offshore regions are excluded in the ERA5 bathymetry data, while water depths are assigned to large onshore regions. According to ECMWF, the same resolution problems arise for the bathymetry, as it is linked to the ocean model. For the US East Coast, one value seems to be assigned to four grid cells similarly. The numerical results confirm this observation. The bathymetry data for three to five grid cells is identical for some areas. This also applies to the bathymetry results of both the German Bight and South Korea. It can be assumed that the bathymetry data is saved on 0.5° x 0.5° resolution. This would correspond to the observations. The results of the bathymetry can therefore only be considered with care or as first, rough estimation.

The results for the German Bight show comparably shallow waters. The major part of the region has water depths of below 50 m. This is a viable depth for fixed bottom offshore wind foundations. In the north west of the reviewed region, outside of the German EEZ, the water depth increases. As fixed bottom wind is not applicable at these water depths, floating solutions may be an option. However, due to the previous criteria, more severe wind and wave conditions occur in this area. This affects the suitability for hydrosensitive floating concept.

For the US East Coast, locations close to the shore have water depths well suited for fixed bottom offshore wind. Within 70 km around the coast, the water depths are approximately 10-40 m. The water depth increases rapidly with higher distances to the coast. Floating solutions are the only viable option here.

In South Korea, the water depths are generally higher than for the German Bight or the US East Coast. Except for regions in direct proximity to the shore, only floating wind might be an option, as the water depths are larger than 140 m for many locations, especially at the east coast. However, taking into consideration the less severe extreme wind and wave conditions, floating wind might be very viable. Based on the high water depths far from shore, nearshore wind farms are planned to use fixed-bottom concepts in South Korea.

Distance to shore

The results for the assessment of the distance to shore is exemplarily shown for the target regions German Bight and South Korea.

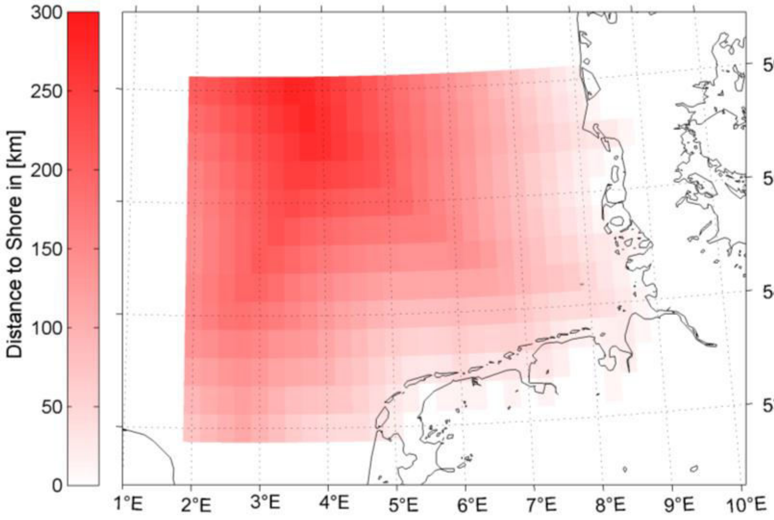

Figure 51: Distance to shore in the target region *German Bight*

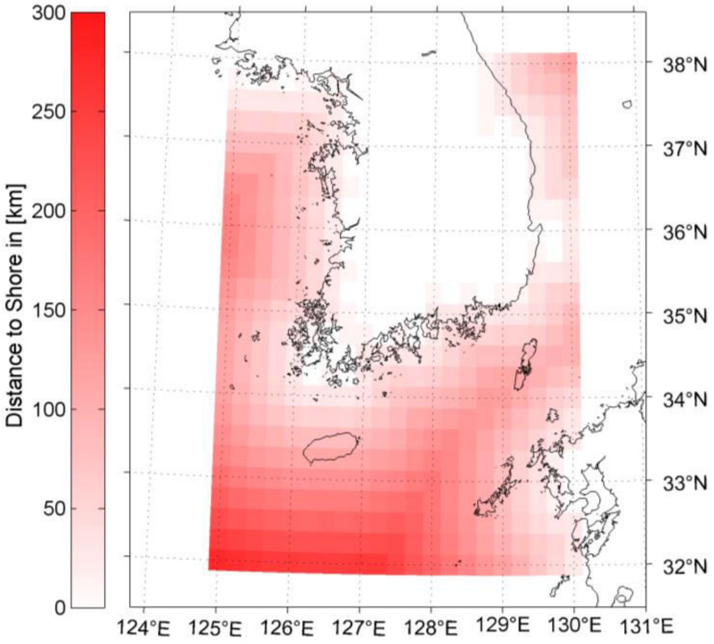

Figure 52: Distance to shore in the target region *South Korea*

The results for the German Bight show that the assessment provides the basis for a reasonable first guess for the estimation of the distance to shore. As the calculation method is based on the bathymetry data, the results for the distance to shore are worse for regions, which are not well covered by the lower resolution ERA5 bathymetry data. An example is South Korea, where the major island Jeju to the south of the Korean mainland is not described correctly by the bathymetry data. Even though, for many grid cells, Jeju island is the closest "shore", it is not represented. These impairments can easily be detected upon reviewing the visualisation of the distance to shore. However, the numerical results of the distance to shore always have to be reviewed in the context of the assessment of the surrounding region.

The distance to shore describes the feasibility of marine operations of different types. For sites with larger distances to shore, specialised vessels or even helicopters have to be considered. In addition to O&M considerations, the distance to shore is also important for the net integration. Larger distances to shore require longer cables and more general installation effort.

6.3.2 Single Sites

In this chapter, the results for the assessment of the single sites are presented. In a first step, the results for the basic criteria for all single sites are presented tabularly and described afterwards. In order to discuss the quality of the results, they are compared to publically available information about the three sites. After the basic criteria, the results of the assessment of the advanced criteria are presented.

Basic Criteria

Table 9: Overview over the results (basic criteria) of the site assessment for the three *single sites* (Offshore Windpark "Sandbank", Vineyard Wind 1, Donghae 1 Floating Wind Farm)

	"Sandbank" *Proven Area*	**Vineyard Wind 1** *Planned Area*	**Donghae 1** *Potential Area*
Mean wind speed	9.95 m/s	9.16 m/s	7.78 m/s
Estimated AEP	40.849 GWh	36.497 GWh	28.557 GWh
Extreme 1-year wind speed	32.85 m/s	26.26 m/s	25.00 m/s
Extreme 50-year wind speed	43.80 m/s	35.02 m/s	33.33 m/s
Extreme 1-year significant wave height	7.3 m	5.8 m	5.0 m
Extreme 1-year individual wave height	13.1 m	11.07 m	N.A.[1]
Extreme 50-year significant wave height	20.0 m	7.9 m	9.0 m
Extreme 50-year individual wave height	30.1 m	15.4 m	N.A.[1]
Accessibility (6 h, Hs≤1.5 m)	54.4 %	63.9 %	75.4 %
Accessibility (12 h, Hs≤1.5 m)	53.3 %	62.9 %	74.6 %
Bathymetry	30 m	42 m	111 m
Distance to shore	96 km	89 km	53 km

The table displays the main differences for the three sites. The advantages and disadvantages of each site can be identified. The European single site, which contains the location of the already operating wind farm *Offshore Windpark "Sandbank"*, has both the highest mean wind

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[1] Due to an error during the ERA5 data download, the individual wave height were not be calculated for the target region *South Korea.*

speed and the highest estimated AEP of all three single sites. According to a press release from May 2016 from Vattenfall, the operator of the wind farm estimated AEP of the entire wind farm amounts to 1.4 TWh [80]. Based on the 72 installed 4 MW wind turbines, this results in approximately 19.5 GWh annual energy production per 4MW-OWT or 39 GWh per 8 MW installed capacity. This actual data is very close to the results of the site assessment calculation, which estimates 40.8 GWh for the 8 MW reference wind turbine. The water depth for the wind farm is listed as 24-33 m [80]. Despite the low resolution of the bathymetry, the result of the site assessment in this work is very accurate and states an average water depth for the grid cell of approximately 30 m. For the distance to shore, the methodology of this work calculates 96.3 km. According to Vattenfall, the actual distance to shore amounts to 110 km to the mainland and 90 km to the island Sylt. Again, the results of the site assessment provide accurate data. The metocean wind and wave results are difficult to compare, as design basis and detailed information about the wind farm are not made publically to the author’s knowledge. In order to compare the results with data from other sources, the New European Wind Atlas (NEWA), an ERANET+ project, which was funded by the European Commission and provides extensive wind data for Europe, was consulted. Based on the NEWA, the mean wind speed for the centre of the grid cell amounts to 9.89 m/s [81]. This is very close to the results of the site assessment of this work, which calculated a mean wind speed of 9.95 m/s.

For the *planned area*, the grid cell containing the location of the planned offshore wind farm Vineyard Wind 1 was assessed. The results consider the windfarm location to be 89 km off the coast of Massachusetts. However, according to the project documentation, the distance to the shore amounts to 15 miles, which corresponds to 24 km [69]. This is a major difference. The reason can be found in the presentation of the bathymetry at the US East Coast in Figure 49. The islands off the coast and even the headland to the north of Vineyard Wind 1 are not recognised as onshore locations by ERA5. This leads to the described error. The bathymetry on the other hand matches the official site descriptions (37-49 m) very well [67]. As for the Offshore Windpark “Sandbank”, no wind or wave conditions are publically available. Though the corresponding documents were made public, the actual data was blackened [82]. Summarising the results of the site assessment of this work, the site provides a solid basis for offshore wind applications. The less severe extreme events in comparison to the site of “Sandbank” effects the design basis for both turbine and foundation positively. However, the higher water depths require adjusted foundations. This may result in larger costs as well. The marginally lower AEP in comparison to the North Sea site was predictable due to the lower mean wind speed. Still, the wind resources of the site are considerable high.

The results for the grid cell with the location of the Donghae 1 Floating Wind Farm off the east coast of South Korea define the site as a site with lower wind speeds and sea states. The mean wind speed is considerably lower compared to the other two sites; also, the extreme events for both wind and waves are also considerably in the most cases. This also results in the accessibility being the highest among the three reviewed sites. Due to the high water depths, only floating wind concepts are possible. The less harsh metocean conditions suit floating wind particularly well, as floating wind is hydrodynamically more sensitive than fixed bottom wind. Though the 1-year extreme significant wave heights are the lowest among all three sites, the 50-year significant wave height is higher for the Korean site than for the American site. In combination with the generally high accessibility, this indicates that the sea states are usually calmer but shows a higher variance regarding extreme events with high recurrence periods. The results of the site assessment could not be verified in detail, as to the author's knowledge, almost no data about the site is publically available from official sources. The only variable available was the distance to shore, which is stated to be 58 km [83]. This is very close to the result of this work's site assessment, which is 53 km. For another comparison, the results for wind data were compared to those of *The Global Wind Atlas*. The result of this work's methodology for the mean wind speed is 7.78 m/s, while *The Global Wind Atlas* estimates 7.77 m/s for the same location [7].

Advanced Criteria

The results for the advanced criteria of the site assessment provide a more in-depth evaluation of the three single sites. To compare the three single sites, the results for all three sites are summarised in one figure, if possible.

Weibull distribution

Within the site assessment of this work, detailed wind speed probability density functions are derived for the three single sites based on two-parameter Weibull distributions. The following diagram shows the three distributions. The dashed lines show to the mean wind speeds of the corresponding site.

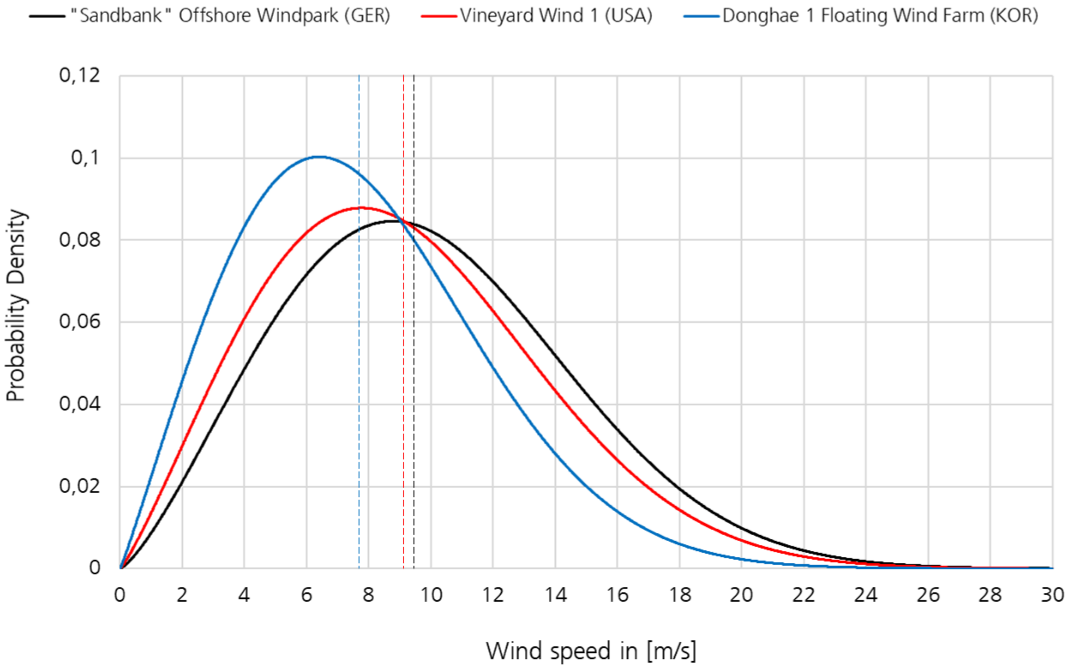

Figure 53: Wind speed probability density functions (Weibull distributions) for the three *single sites* (Offshore Windpark “Sandbank”, Vineyard Wind 1, Donghae 1 Floating Wind Farm) [dashed lines visualise the mean wind speeds at the corresponding site]

The wind speed probabilities confirm the results of the evaluation of the basic criteria. The highest wind speeds are expected at the site of the Offshore Windpark “Sandbank”. At the Korean site, the wind speeds are considerably lower. The probability functions are especially valuable when compared to the power curve of the intended wind turbine, as in this case: the power curve of the LEANWIND 8MW reference wind turbine (Figure 11). The comparison shows that – based on the reference wind turbine – besides the higher mean wind speeds, the probabilities for full-load operation are also significantly higher for the location of the Offshore Windpark "Sandbank" in comparison to especially the South Korean site. Based on such a comparisons with power curves, the probability functions can support the selection of a wind turbine for a potential site. For the Donghae 1 project for example, a turbine model with the possibility of full-load operation at lower wind speeds should be considered.

Wind Roses

Beside the evaluation of the wind speed probability, the site assessment methodology of this work also provides the evaluation of the wind speed directions. Wind roses are determined from the time series. The directional component of the wind is important for the planning of the wind farm layout. In addition, the knowledge of the wind speed directions provides further information for a complete characterisation of wind resources at the assessed site. The following diagram shows the wind roses for the three sites.

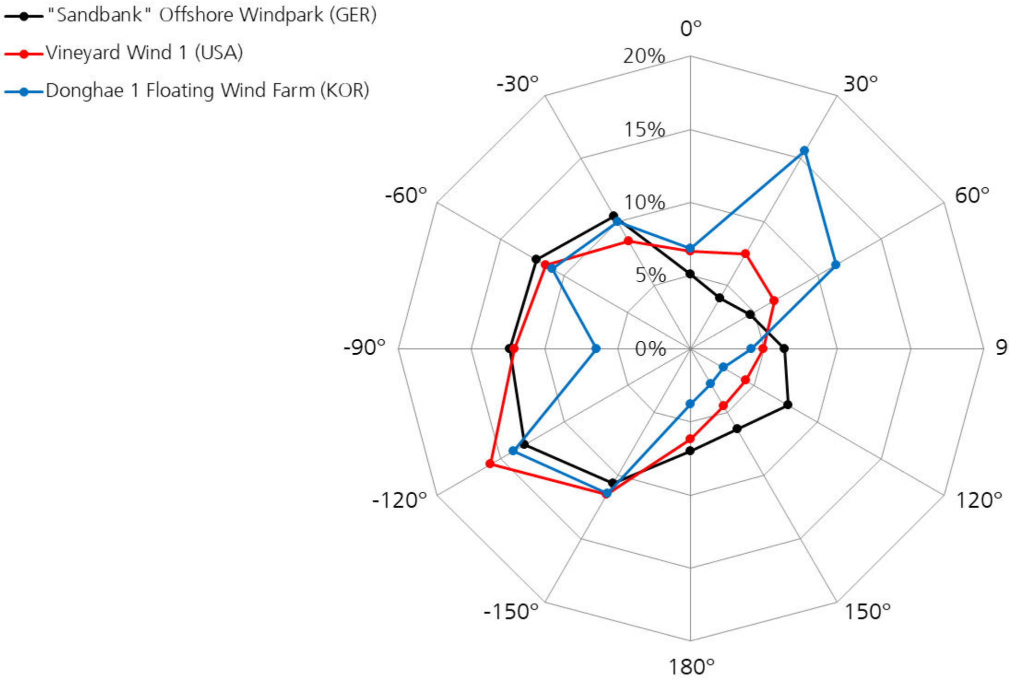

Figure 54: Wind roses (wind direction probabilities) for the three *single sites*
(Offshore Windpark "Sandbank", Vineyard Wind 1, Donghae 1 Floating Wind Farm)

The diagram shows the wind direction distributions; these can vary from site to site, not only regarding the main wind direction but also regarding the shape of the wind rose. In the context of the geographical location of the Offshore Windpark “Sandbank” (Figure 17) the major share of the wind is coming from the sea (onshore wind). For the site of Vineyard Wind 1, the major share of the wind is either parallel to the shore or coming from the shore (offshore wind). The site of the planned floating wind farm Donghae 1, the wind directions appear to be split between three directions. The wind is either directed parallel to the coast, either towards the north east or towards the south west or directed towards the open sea.

The post-processor of the methodology not only evaluates the cumulative wind directions but also distinguishes the directions for different wind speed bins. The more detailed wind roses are presented exemplarily for the location of the Offshore Windpark “Sandbank”.

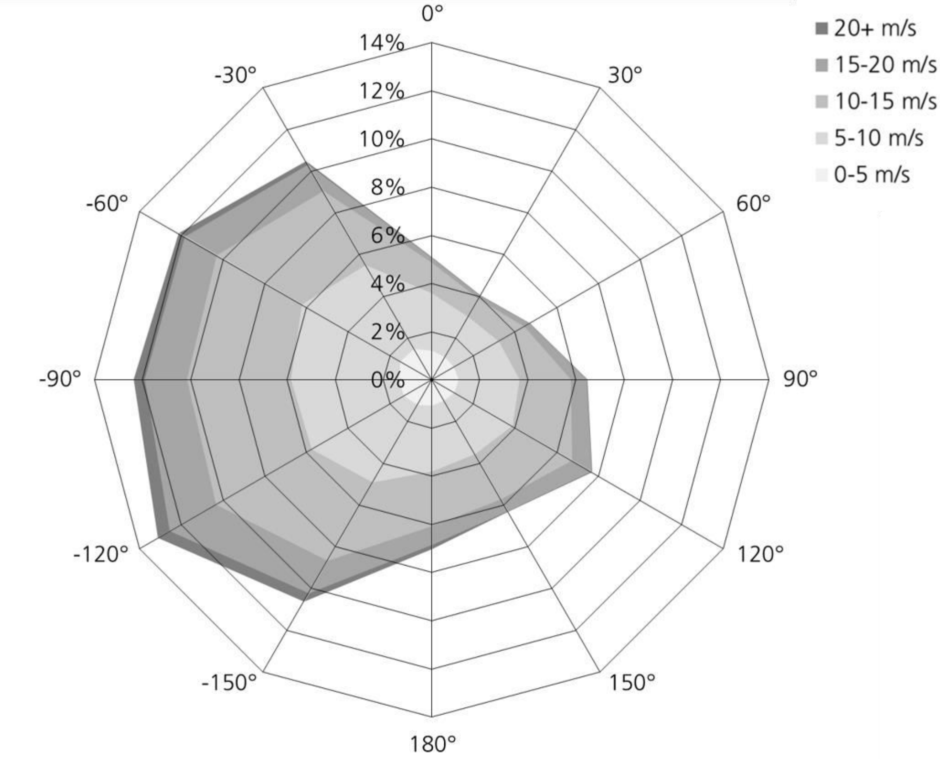

Figure 55: Detailed wind rose for the single site *Offshore Windpark “Sandbank”*

This more detailed wind rose allows the combined interpretation of the wind direction distribution and the wind speed distribution. It also helps to detect anomalies. For example, the high share of a certain wind direction may be caused by wind speeds outside of the power production range of the turbine. This would influence a possible park layout. This more detailed wind rose also lays the basis for a potential energy rose.

Wind-Wave-Misalignment

By comparing the wind directions with the wave directions, another relevant criterion was calculated for the three single sites during the site assessment: the wind-wave-misalignment. The results for this criterion are presented for all three sites.

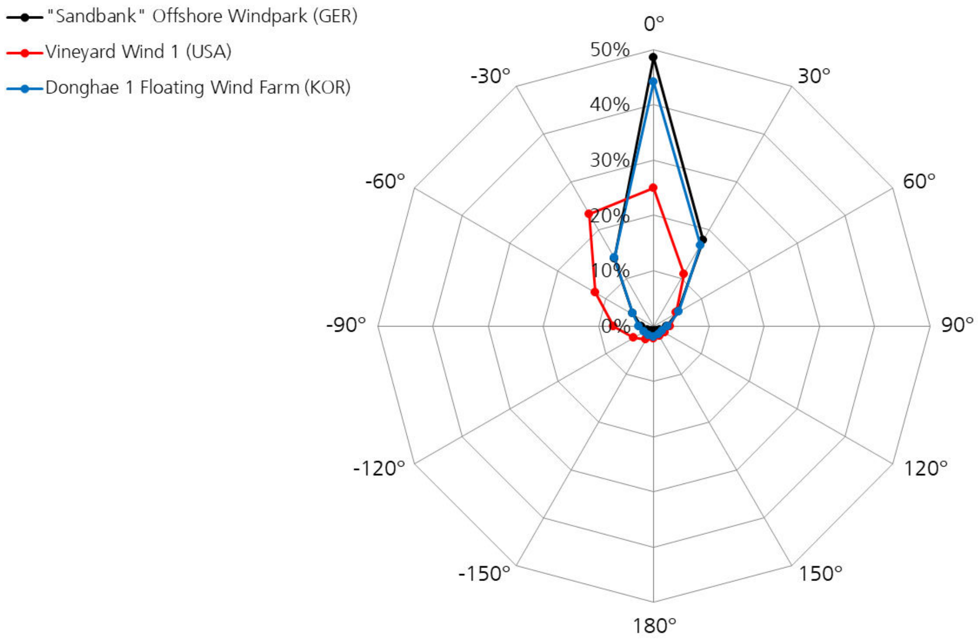

Figure 56: Wind-wave-misalignment distribution for the three *single sites*
(Offshore Windpark "Sandbank", Vineyard Wind 1, Donghae 1 Floating Wind Farm)

The diagram shows that for both the site in the German Bight and the South Korean site, wind and waves are directed in the same direction. This is especially valuable for the Donghae 1 Floating Wind Farm, as floating wind is more hydrodynamically sensitive due to its additional degrees of freedom. For the site of Vineyard Wind 1, wave directions are more often not in line with the wind directions. Here, waves are mostly directed in the same direction like the wind or is yawed 30° to the main wind direction.

7 Conclusion

In this work, a site assessment methodology was developed. In the begining, the work has been classified within the context of existing site assessment methodologies, the metocean data basis has been explained and reviewed and the criteria set has been developed based on standards and the input of experts. The functionalities and the possible results of the methodology were presented exemplarily in the case studies. In this chapter, the functionalities and the quality of the methodology are reviewed. This leads to an overall valuation of the methodology and an outlook, which includes possible next steps.

7.1 Review of the Methodology

The methodology meets the requirements, which were defined in the scope of this work. It is globally applicable and provides the results and the information, which are required for a preliminary rating of a target region or site regarding its feasibility for offshore wind purposes. The methodology itself does not include the interpretation of the results. The criteria set is based on metocean parameters, which are calculated using ERA5 hindcast data.

The methodology has clear strengths. The selection of the criteria set and its division into basic and advanced criteria is one of these strengths. While the criteria set is very comprehensive and does not miss offshore-wind-relevant metocean conditions, the division of the criteria into the two categories supports a quick assessment and characterisation of the site. The basic criteria provide enough data to develop a profound first impression of the site. They include the most relevant criteria regarding offshore wind siting. The possibility to review them in maps in the context of the surrounding region helps to rank the assessed site. The advanced criteria provide further insight of the site. The level of detail of the information provided by the advanced criteria is much higher than for the basic criteria. This enables are more profound discussion and comparison of individual sites.

Another strength is the quality of the presentation methods. The maps are precise and clear as they assign the results unambiguously to the corresponding locations. They enable a comparison of the parameters at first sight. The implementation of the mapping allows to apply customised scales to support the intended focus or the project specifications. This also enables the user to compare different regions from all around the globe easily. One reason for the quality of the maps is the usage of the *M_Map* toolbox [52]. It allows to directly convert the resulting MAT-data to graphics and maps without the use of any other commercial software.

Another main strength is the quality of the results. Even though, no comprehensive validation of the results has been conducted within this work, all results, which were compared to data from other sources, were accurate. Despite the spatial averaging of the ERA5 data, for the compared sites, the results were very similar. This applies to the AEP and the mean wind speed but also to the bathymetry and the distance to shore. Though the bathymetry is provided at a lower resolution, which also affects the distance to shore, for the example sites, no major discrepancies could be identified. The exemplarily conducted comparisons do not replace a comprehensive validation of the ERA5 data. However, at first site, it attests the high performance of this work’s site assessment methodology.

Beside the strengths, the methodology also has weaknesses. One of the weaknesses is the resolution of the model grid and especially the bathymetry. Though it was not apparent in the ERA5 documentation, the results of the case study suggest a resolution of 0.5° x 0.5° for the bathymetry. This is not only a much lower resolution than the wind and wave data, but also affects the calculation of the distance to shore, which is implemented as the distance to the closest grid cell with a water depth of 0 m. The lower resolution of the bathymetry results in a higher uncertainties for the estimation of both the bathymetry at the site and the corresponding distance to shore. A possible solution would be to use bathymetry data from other sources with a higher resolution. Nevertheless, the results are a first rough estimation.

Another weakness is the lack of wind turbulence data within the model data. It is known that at the model resolution of 0.25° x 0.25° no profound statement can be made about the wind turbulence as it is a local parameter. Still, due to its relevance for the design of wind turbines in IEC 61400, information about the wind turbulence would be important for an even more comprehensive basis for site assessment [32].

The third weakness of the methodology is the missing causal chain for anomalies. For example, the causes for a high individual wave height in a single grid cell are not always available or apparent. In order to interpret the extreme events, the causes may be required. Unfortunately, they are based on the ECMWF reanalysis model. In order to provide a more profound basis for the interpretation of the anomalies, a more profound understanding of the reanalysis model is required. This, however, goes beyond the scope of a preliminary site assessment. In addition to the complexity of the reanalysis model, there is another problem when deriving data regarding extreme events. Reanalysis models often do not include a comprehensive and correct modelling of unusual events like for example hurricanes. For areas with a high occurrence probability of such events, additional uncertainty estimations need to be included [76].

The last main weakness of the methodology is the duration of the calculation. Including the ERA5 NetCDF-download via CDS API, the entire methodology requires about one week of calculation time to provide results for a certain site or region. This time framework may vary for different site or region sizes. However, the temporal performance of the methodology should be improved to also improve its applicability.

The different main strengths and weaknesses of this work's site assessment methodology are summarised in the following table.

Table 10: Overview over the main strengths and weaknesses of the site assessment methodology of this work

Strengths	Weaknesses
Included criteria Provides a comprehensive overview over the reviewed site	***Low bathymetry resolution*** Results into more inaccurate data of both bathymetry and distance to shore
Division of the criteria set into basic and advanced criteria Overview at first site and more in-depth assessment are divided: no information overload	***Unavailability of wind turbulence data*** Main IEC 61400 design parameter is missing
Visualisation style of the results Facilitates a quick and precise comparison	***No explicit explanation of anomalies*** No review of the reanalysis model is included in the methodology, which may impede the interpretation of the results
Quality of the results Comparison with other sources shows a high accuracy of the results	***Duration of the calculation*** The methodology requires large amounts of time, which may impede its applicability for the use case

7.2 Outlook

In this section, possible next steps to improve the results of this work or to extent the scope are presented. An obvious first step is the validation of the ERA5 hindcast dataset. Though it is a product of a renowned organisation in the field of metocean modelling, the ECMWF, a specific validation of the data, which was used in this work, should be conducted to further validate the methodology. Ideally, this validation is conducted for both the ERA5 data itself and the results from this work. There are already several studies, which aim to identify general ERA5 tendencies and biases and rate its overall performance. However, even studies related to wind applications do not cover all the metocean conditions, which were used in this work [25]. The validation of ERA5 should especially rate its performance based on the regarded location. It has to be ensured that the methodology works similarly well for the entire globe.

Another approach to improve the applicability of the site assessment methodology is further development of the automation. Within this work, both the pre-processor and the solver work automated. An obvious next step is to create scripts with a clear graphical user interface to also allow the application of the methodology without specific knowledge of all scripts. This improvement of the automation should also focus on the improvement of the temporal performance, as this is one main weakness of the methodology.

During the evaluation of the ERA5 input data, different additional site information can be derived, such as energy roses or seasonal wind speeds and wave heights. These information were not included in methodology of this work, as they do assess the site in a much more detailed way. A possible extension of this work's methodology could therefore be to also implement the calculation of criteria, which allow for a more detailed site assessment.

Finally, the site assessment methodology of this work could be improved by including additional input data from other sources. Especially for the bathymetry, a source with a higher resolution may be favourable for the methodology as this would also affect the accuracy of the distance to shore. Another highly required parameter is the wind turbulence. With the addition of this parameter, all main IEC 61400 parameters for the validation of the Wind Turbine Class would be provided.

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Appendix A – ERA5 Parameters

The following table, all ERA5 parameters, which are used in the site assessment methodology of this work are presented.

Table A.1: List of the ERA5 parameters, which are used in the site assessment methodology of this work

Parameter	ERA5 Short Name	Unit
Eastward component of the horizontal wind speed at 100 metres above the surface of the earth	100u	[m/s]
Northward component of the horizontal wind speed at 100 metres above the surface of the earth	100v	[m/s]
Significant height of combined wind waves and swell	swh	[m]
Expected maximum individual wave height	hmax	[m]
Mean direction of ocean/sea surface waves	mwd	[degree]
Bathymetry (depth from the surface to the bottom of the ocean)	wmb	[m]

Appendix B – Case Study Example Sites

In this appendix, the grid cells for the target regions US East Coast and South Korea are presented.

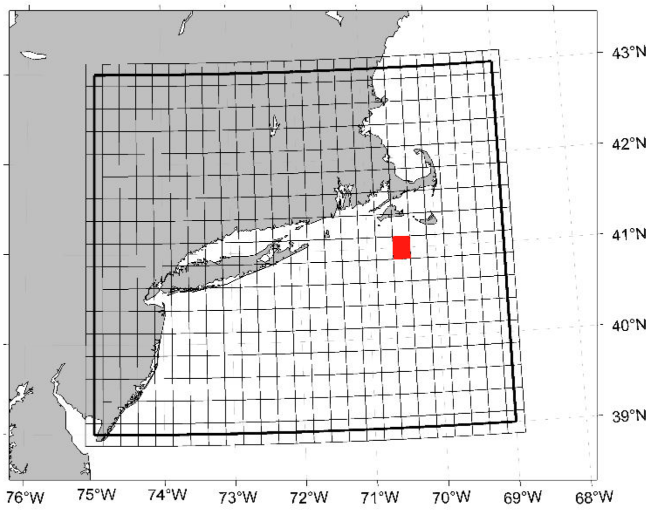

Figure B.1: Grid cells for the target region US East Coast (red=grid cell containing the single site *Vineyard Wind* 1)

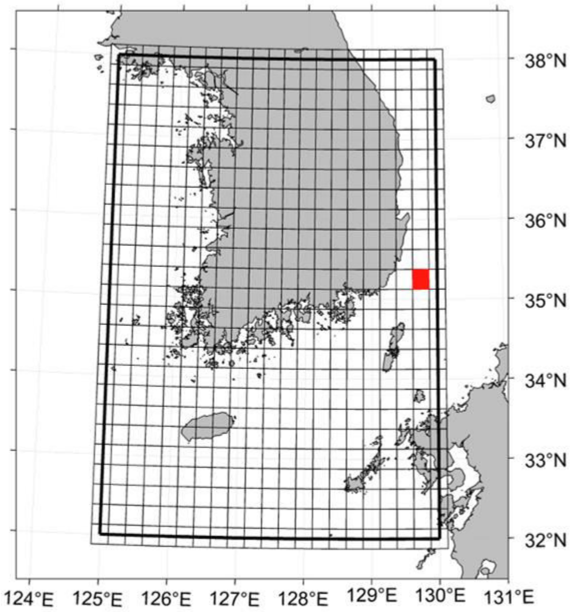

Figure B.2: Grid cells for the target region South Korea (red = grid cell containing the single site *Donghae 1*)

Appendix C – Case Study Results

In this appendix, the results of the case study for all three example sites are presented.

Proven Area – German Bight, Offshore Windpark „Sandbank"

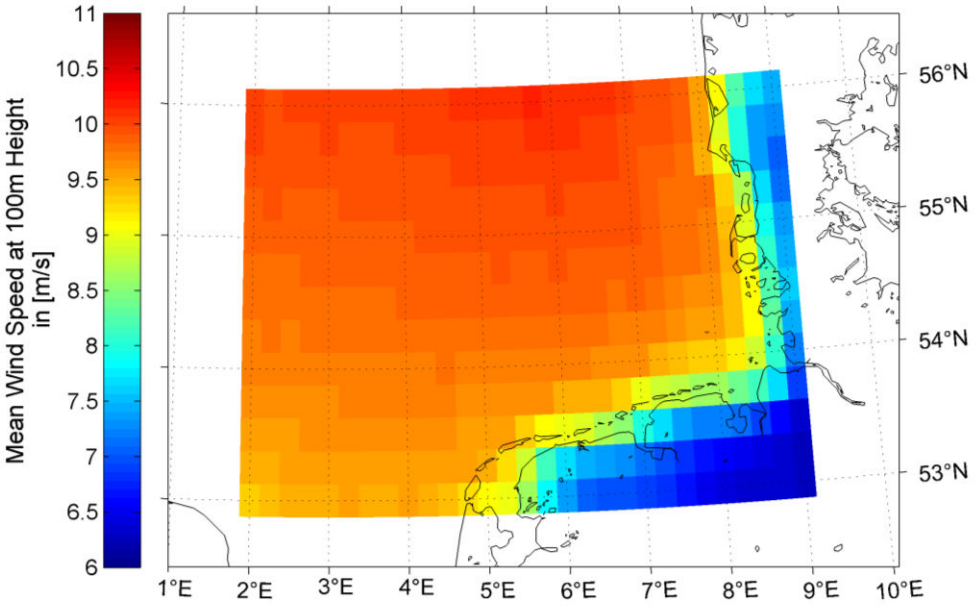

Figure C.1: Mean wind speeds at 100 m height in the target region *German Bight*

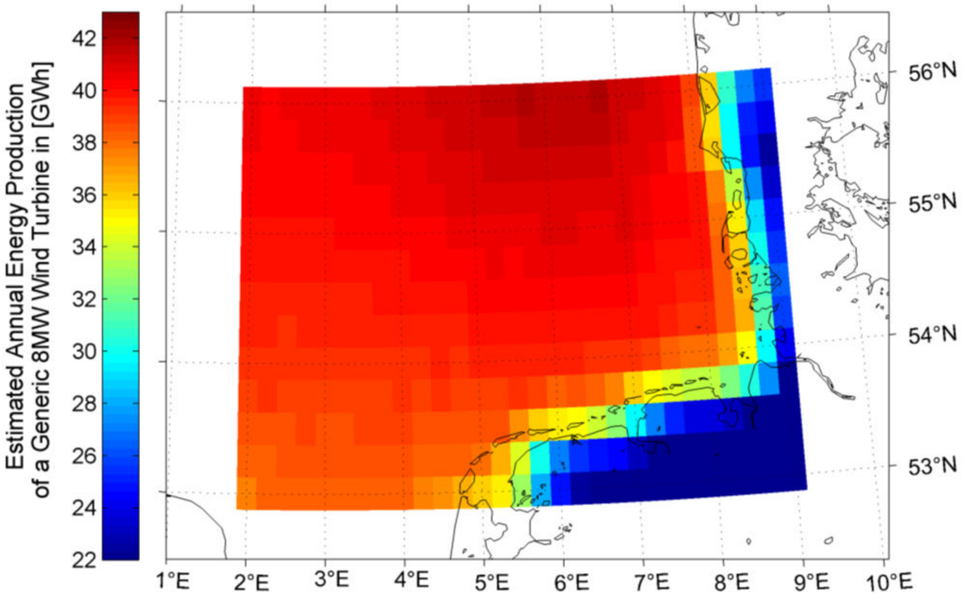

Figure C.2: Estimated Annual Energy Productions (AEP) of the LEANWIND 8 MW reference wind turbine in the target region *German Bight*

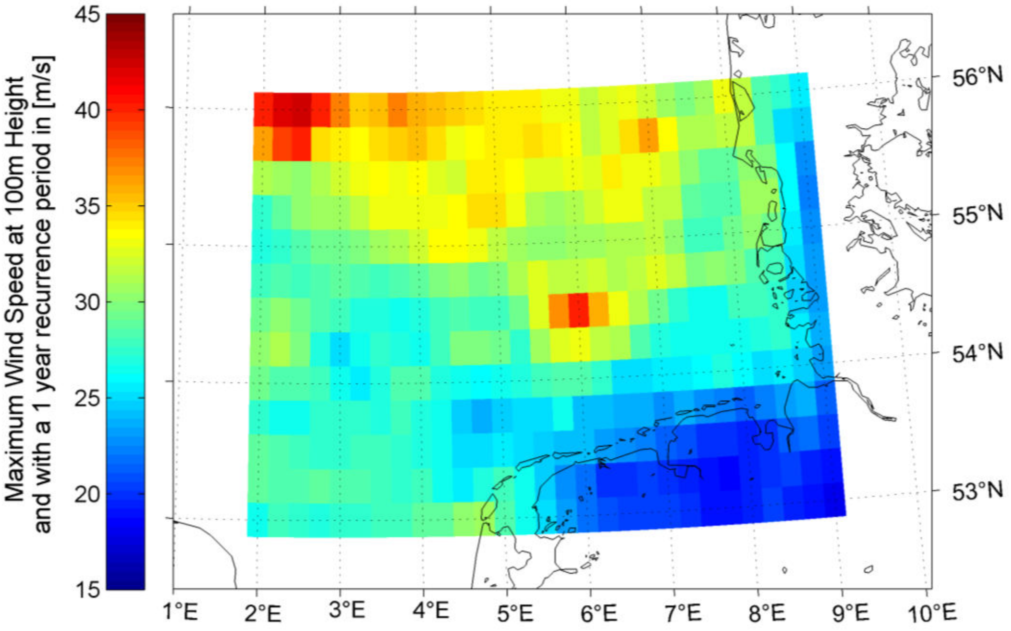

Figure C.3: Extreme 10-min average wind speeds with a 1-year recurrence period in the target region *German Bight*

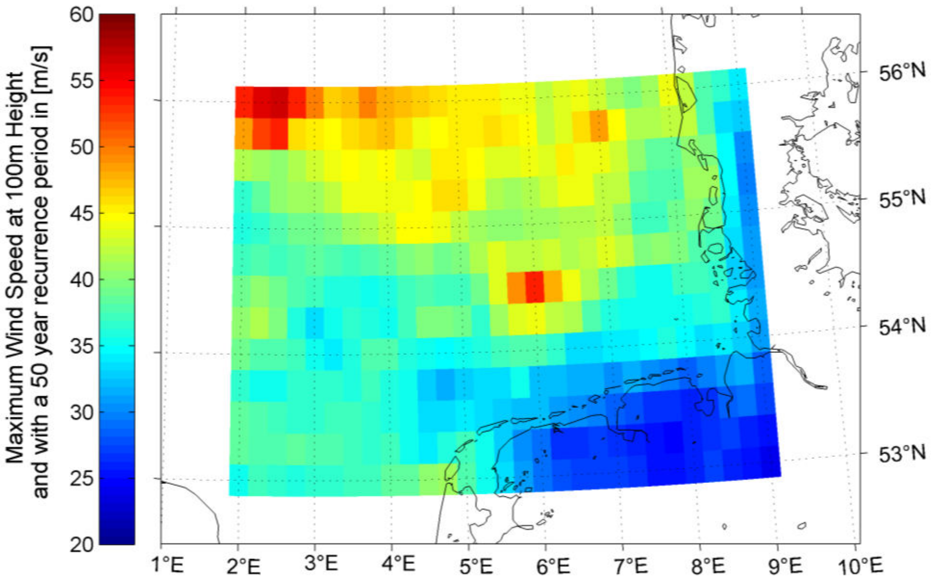

Figure C.4: Extreme 10-min average wind speeds with a 50-year recurrence period in the target region *German Bight*

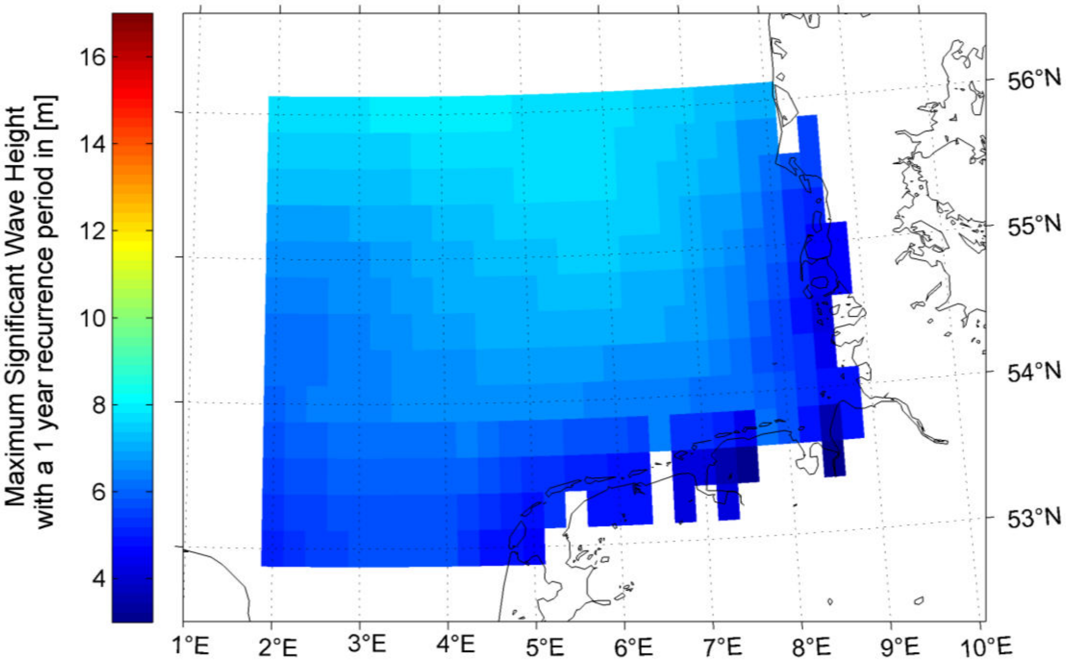

Figure C.5: Extreme significant wave heights with a recurrence period of 1 year in the target region *German Bight*

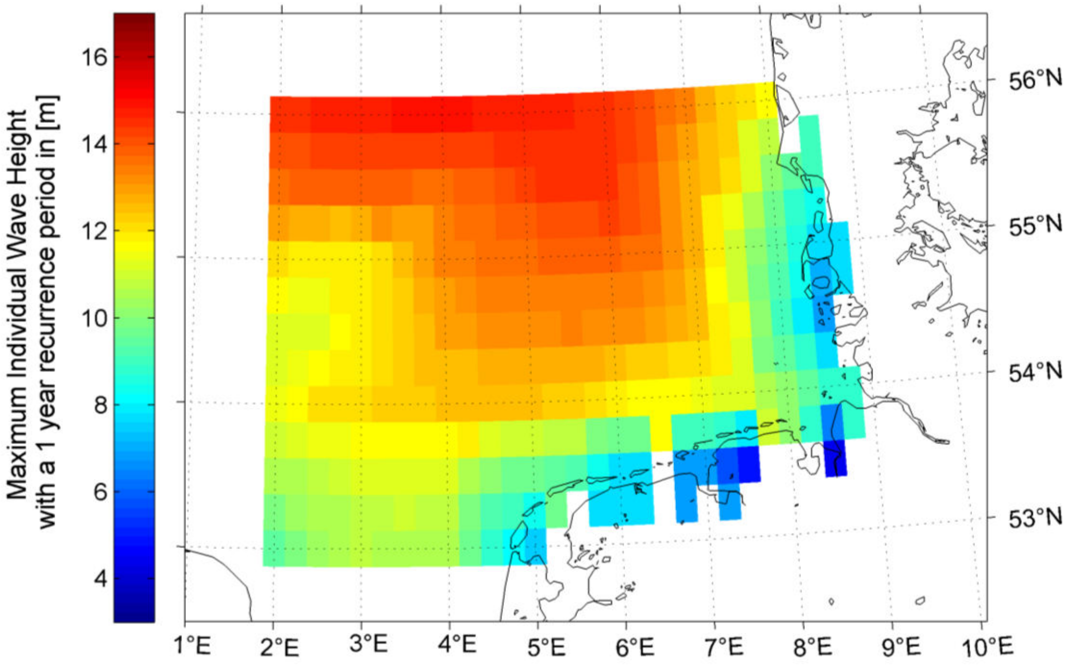

Figure C.6: Extreme individual wave heights with a recurrence period of 1 year in the target region *German Bight*

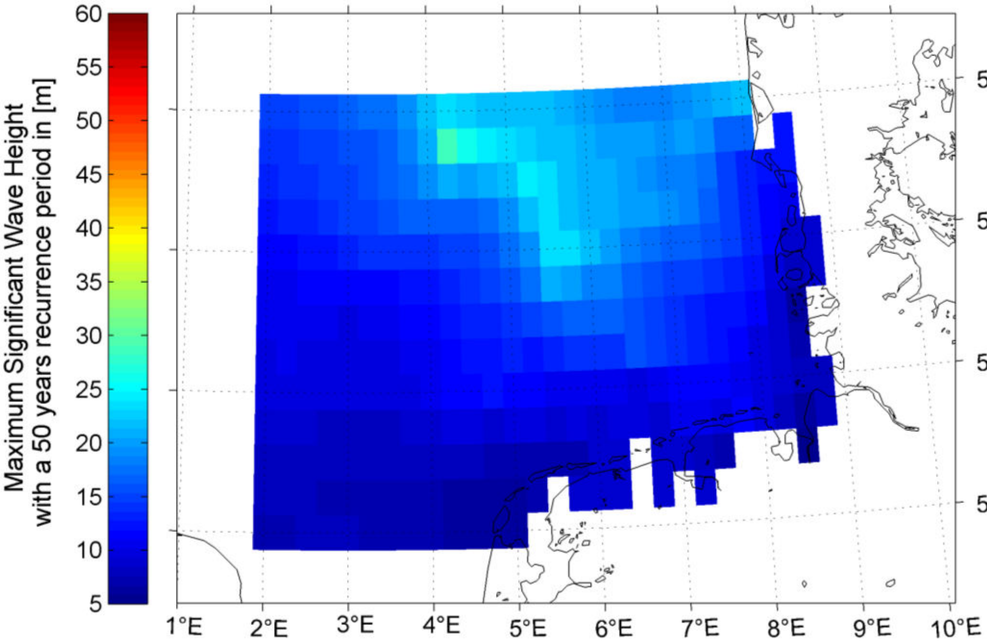

Figure C.7: Extreme significant wave heights with a recurrence period of 50 year in the target region *German Bight*

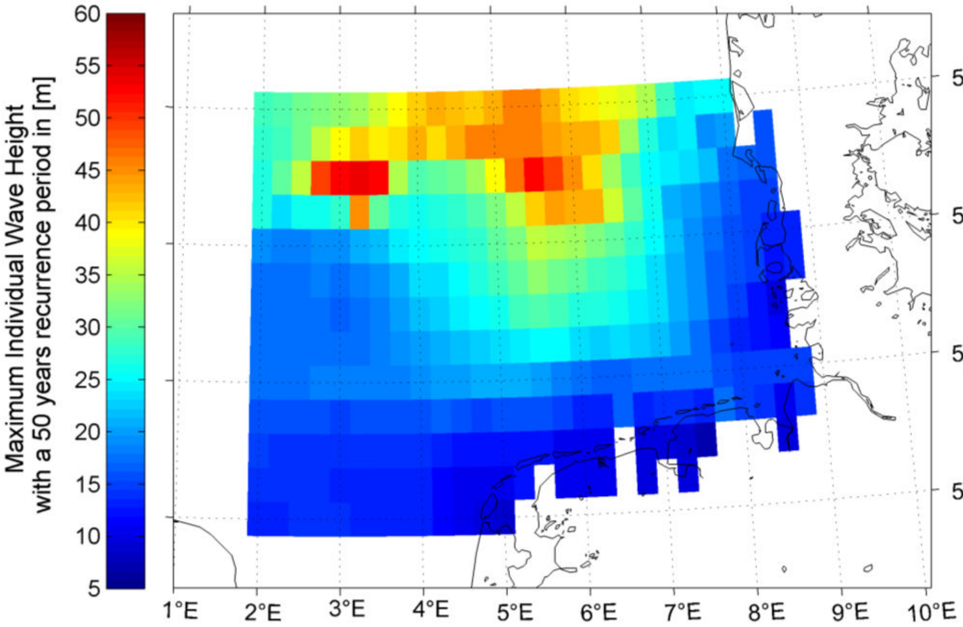

Figure C.8: Extreme individual wave heights with a recurrence period of 50 year in the target region *German Bight*

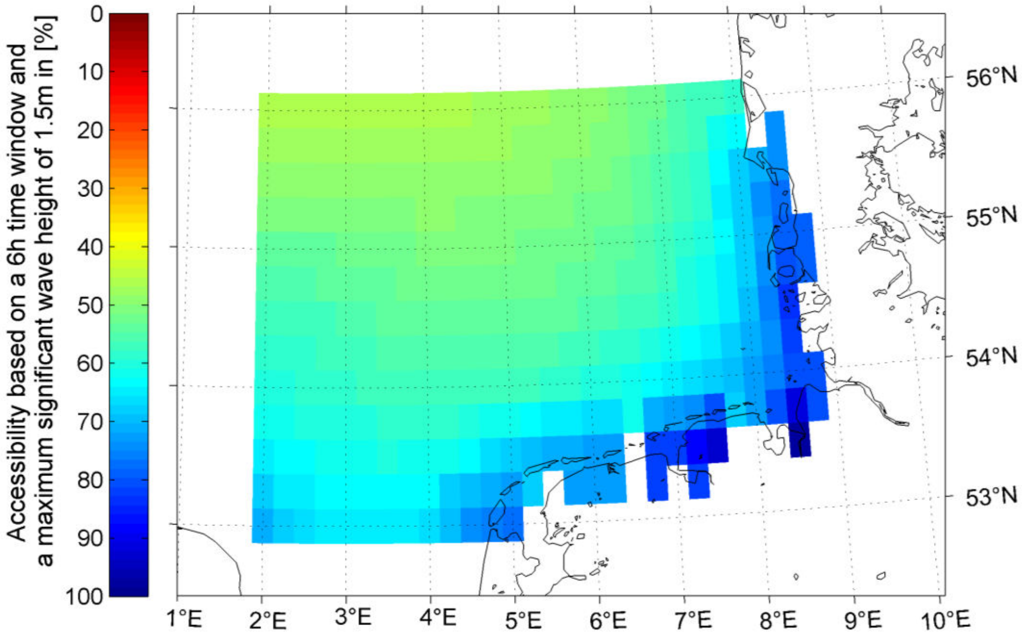

Figure C.9: Accessibilities based on a 6 h weather window (Hs≤1.5 m) in the target region *German Bight*

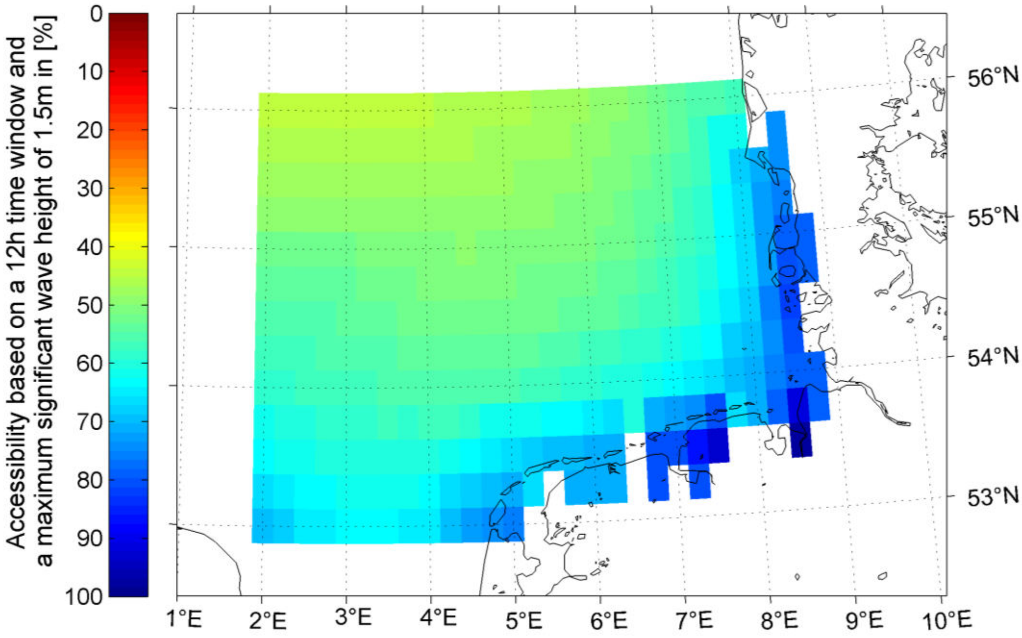

Figure C.10: Accessibilities based on a 12 h weather window (Hs≤1.5 m) in the target region *German Bight*

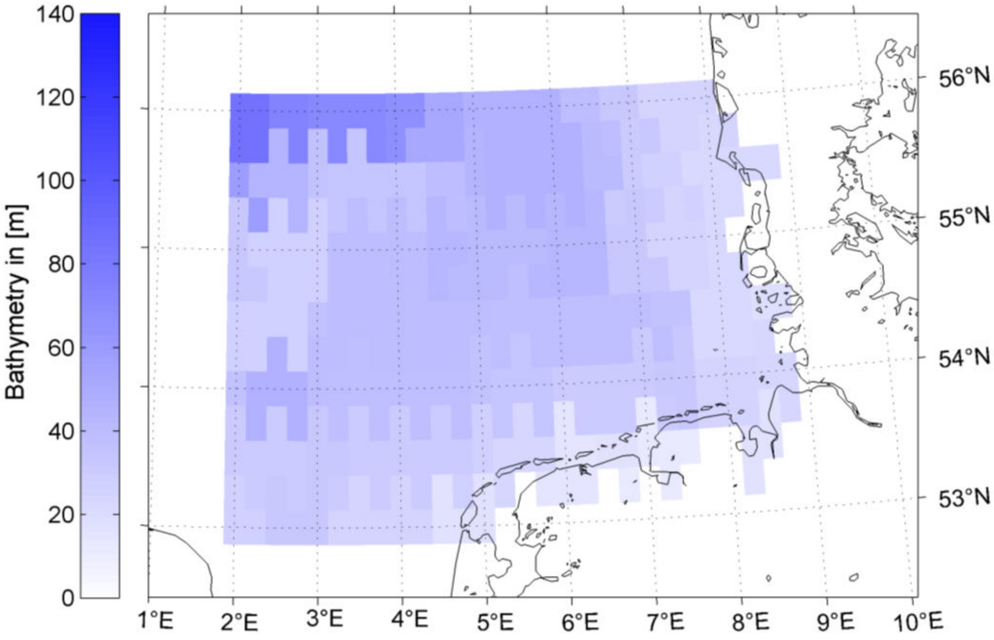

Figure C.11: Bathymetry in the target region *German Bight*

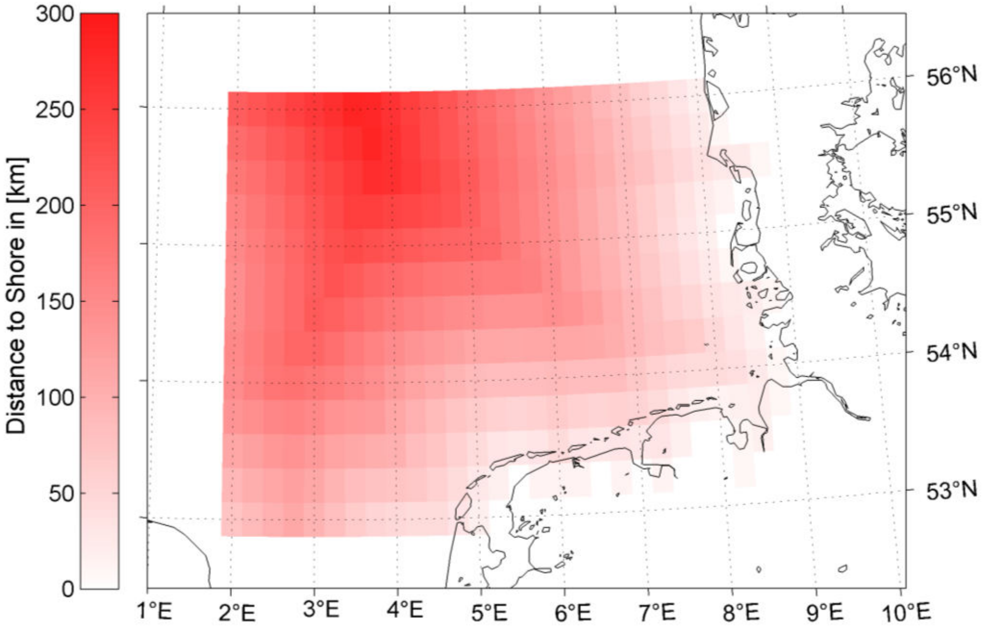

Figure C.12: Distance to shore in the target region *German Bight*

Planned Area – US East Coast, Vineyard Wind 1

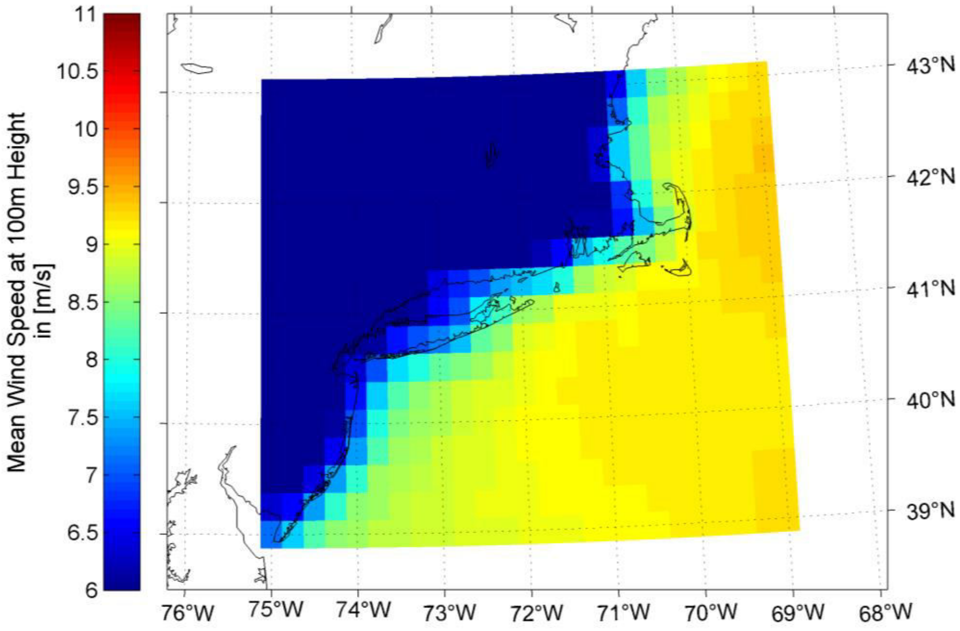

Figure C.13: Mean wind speeds at 100 m height in the target region *US East Coast*

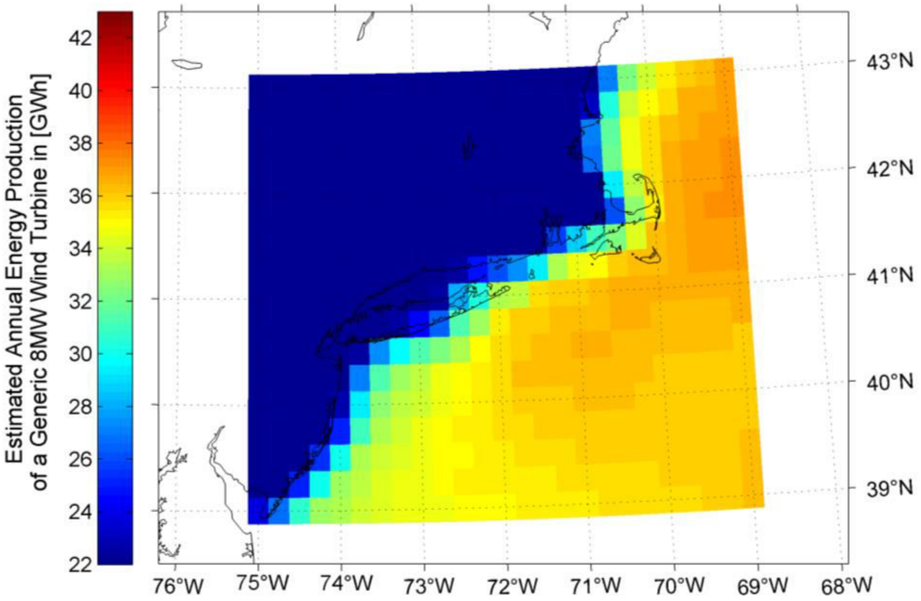

Figure C.14: Estimated Annual Energy Productions (AEP) of the LEANWIND 8 MW reference wind turbine in the target region *US East Coast*

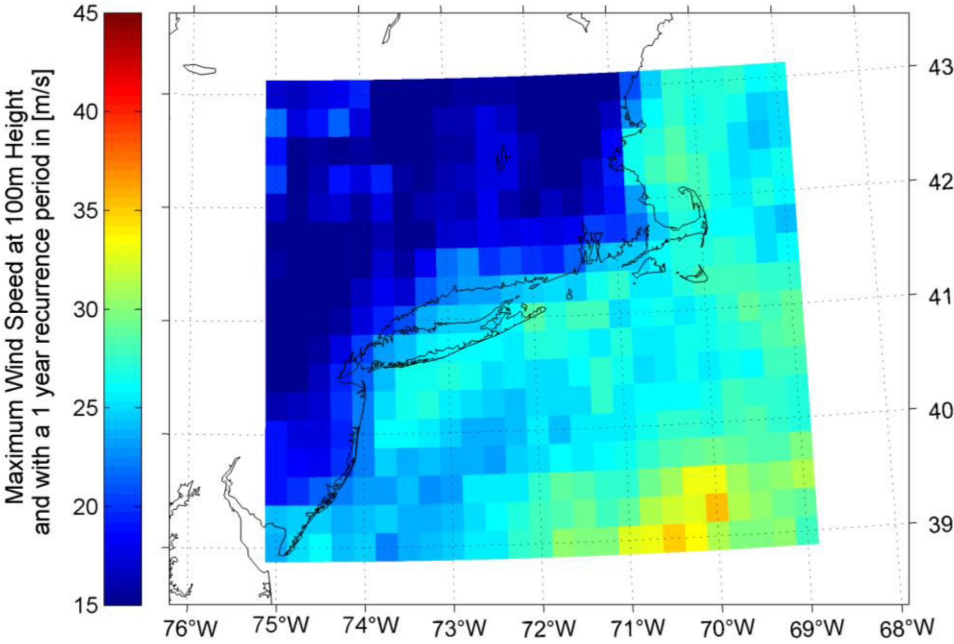

Figure C.15: Extreme 10-min average wind speeds with a 1-year recurrence period in the target region *US East Coast*

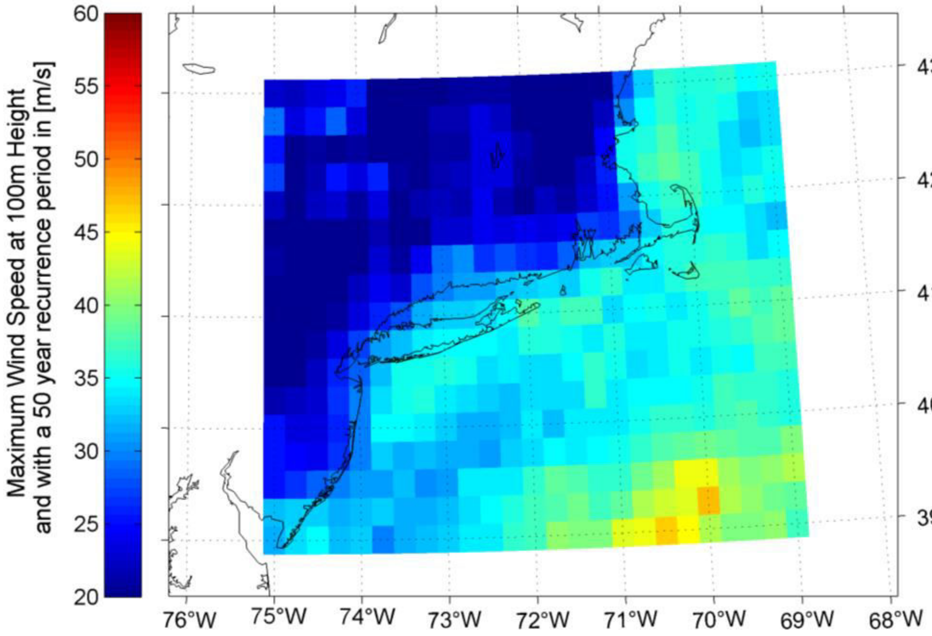

Figure C.16: Extreme 10-min average wind speeds with a 50-year recurrence period in the target region *US East Coast*

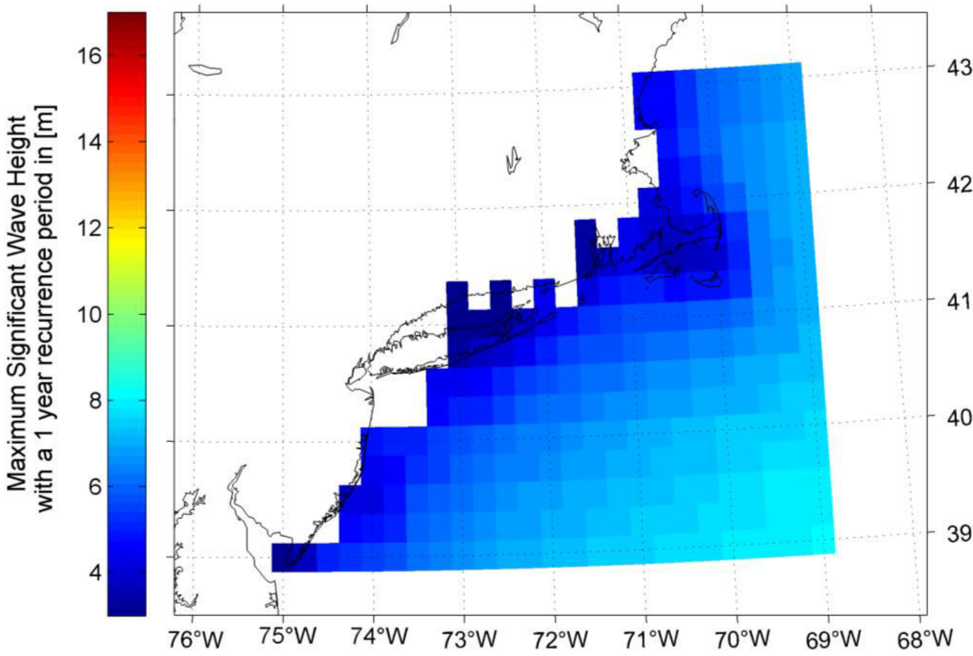

Figure C.17: Extreme significant wave heights with a recurrence period of 1 year in the target region *US East Coast*

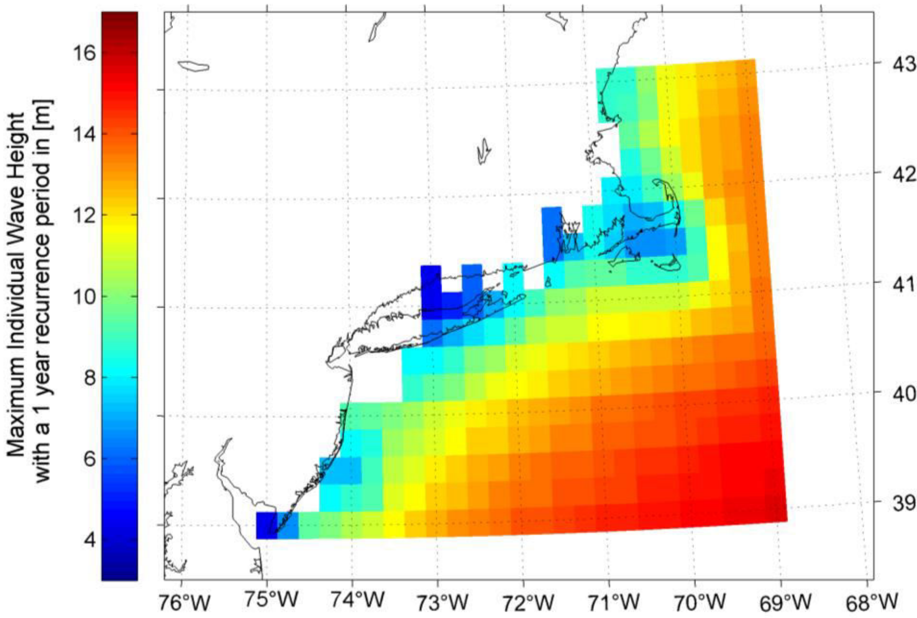

Figure C.18: Extreme individual wave heights with a recurrence period of 1 year in the target region *US East Coast*

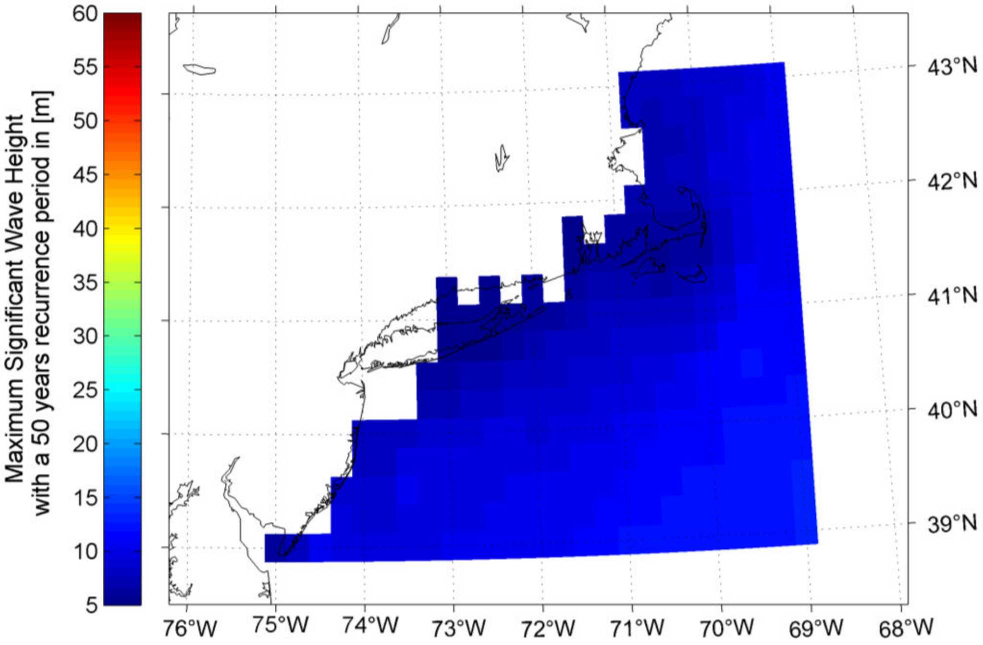

Figure C.19: Extreme significant wave heights with a recurrence period of 50 year in the target region *US East Coast*

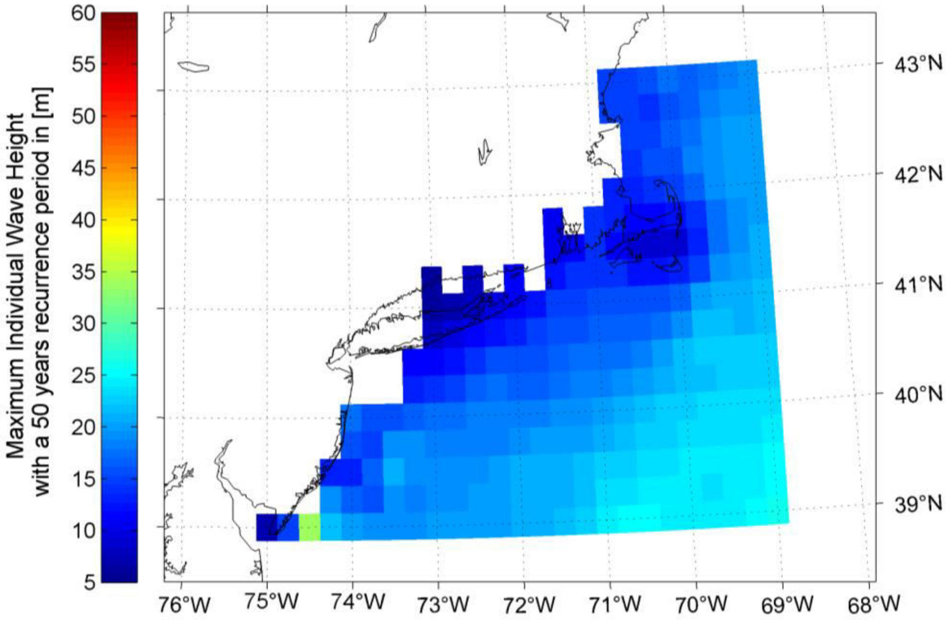

Figure C.20: Extreme significant wave heights with a recurrence period of 50 year in the target region *US East Coast*

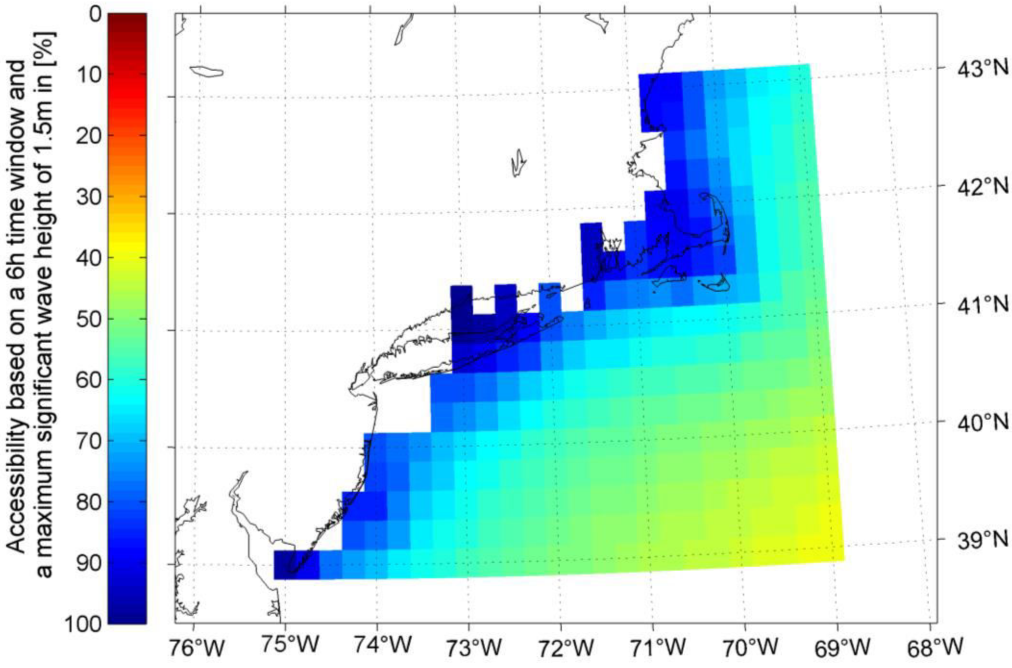

Figure C.21: Accessibilities based on a 6 h weather window (Hs≤1.5 m) in the target region *US East Coast*

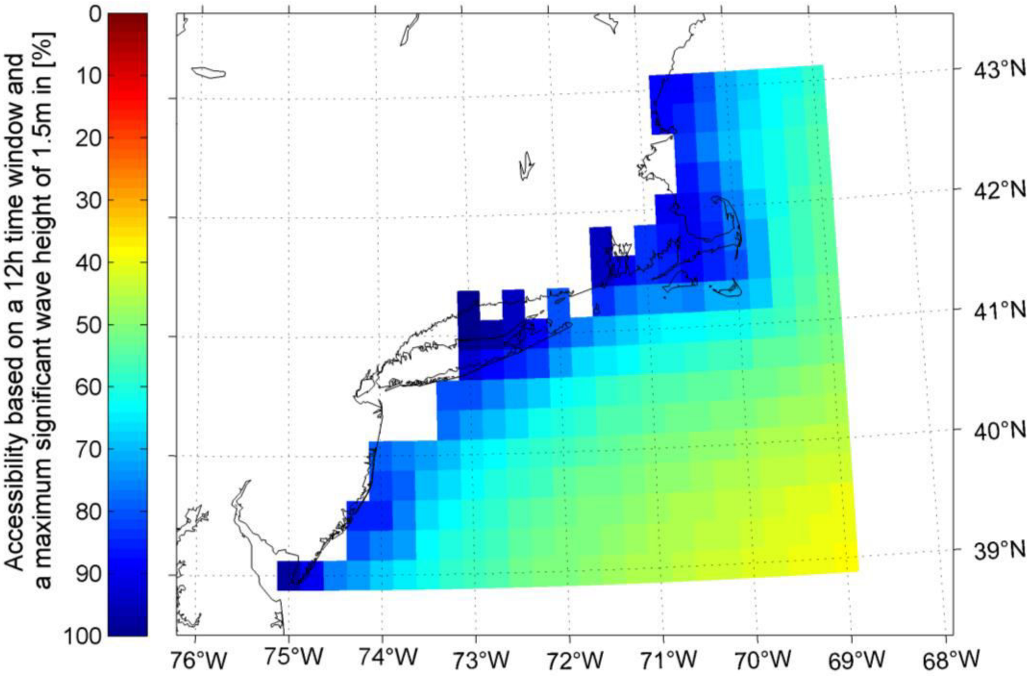

Figure C.22: Accessibilities based on a 12 h weather window (Hs≤1.5 m) in the target region *US East Coast*

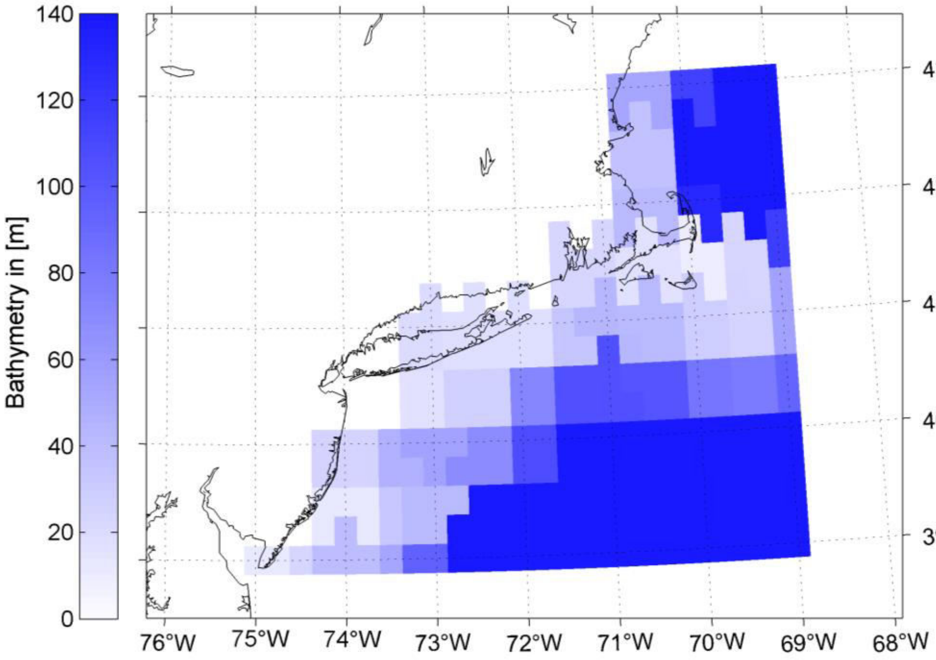

Figure C.23: Bathymetry in the target region *US East Coast*

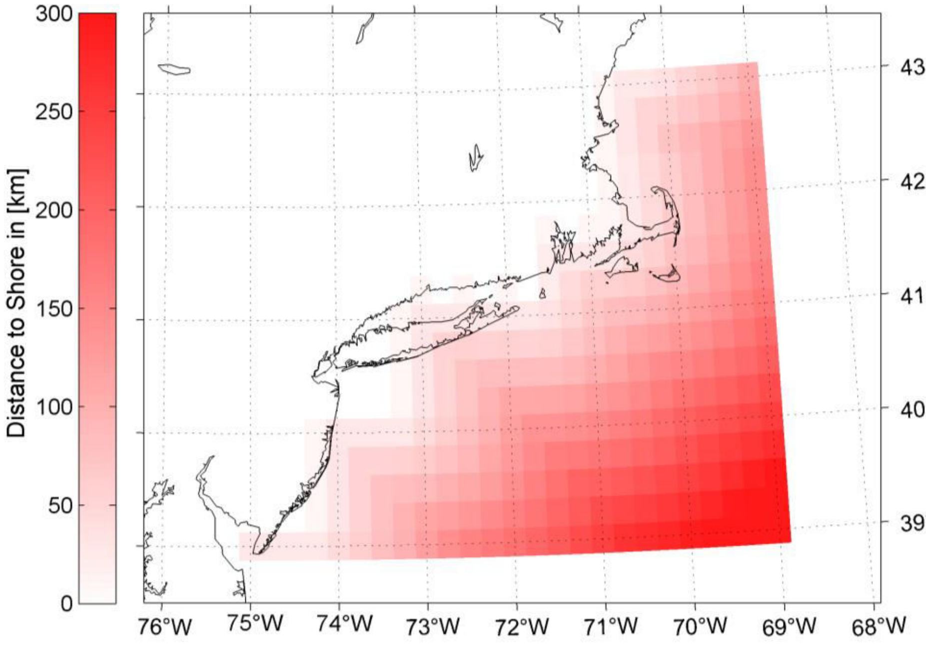

Figure C.24: Distance to shore in the target region *US East Coast*

Potential Area – South Korea, Donghae 1 Floating Wind Farm

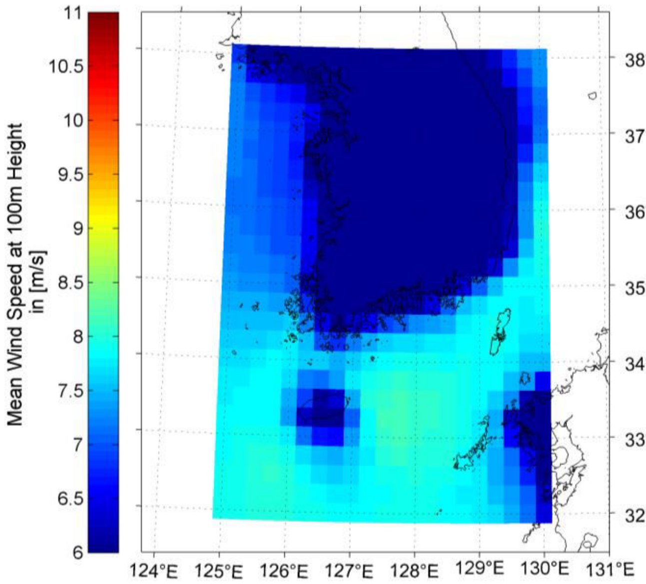

Figure C.25: Mean wind speeds at 100 m height in the target region *South Korea*

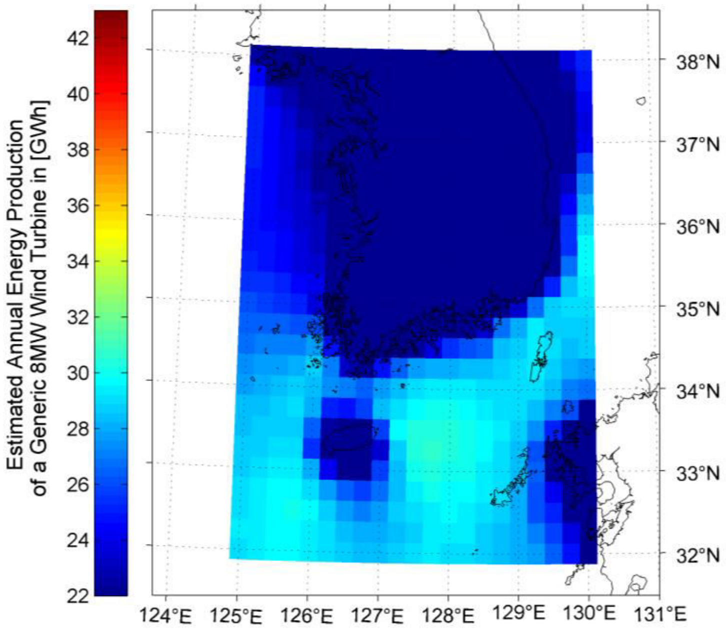

Figure C.26: Estimated Annual Energy Productions (AEP) of the LEANWIND 8 MW reference wind turbine in the target region *South Korea*

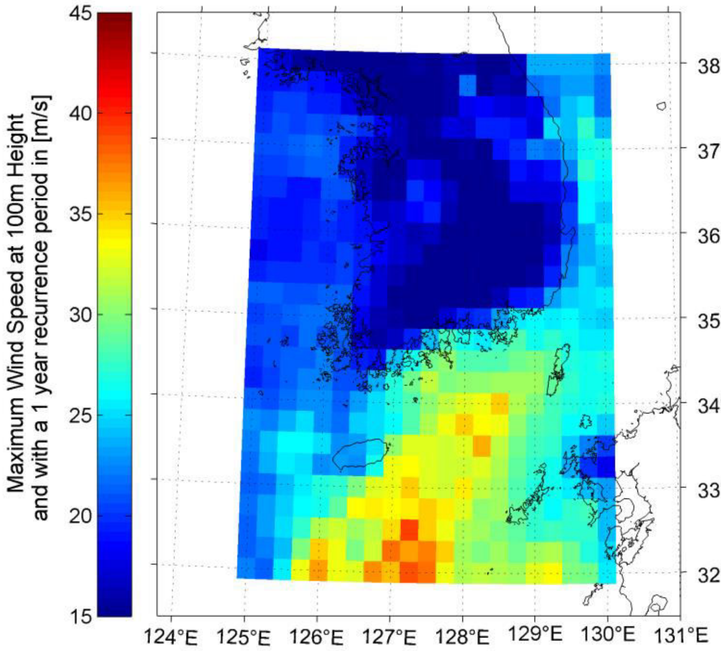

Figure C.27: Extreme 10-min average wind speeds with a 1-year recurrence period in the target region *South Korea*

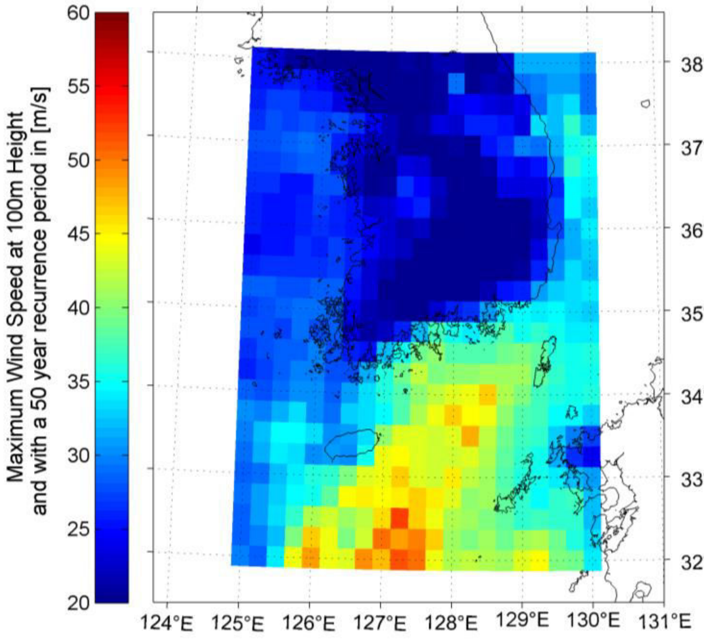

Figure C.28: Extreme 10-min average wind speeds with a 50-year recurrence period in the target region *South Korea*

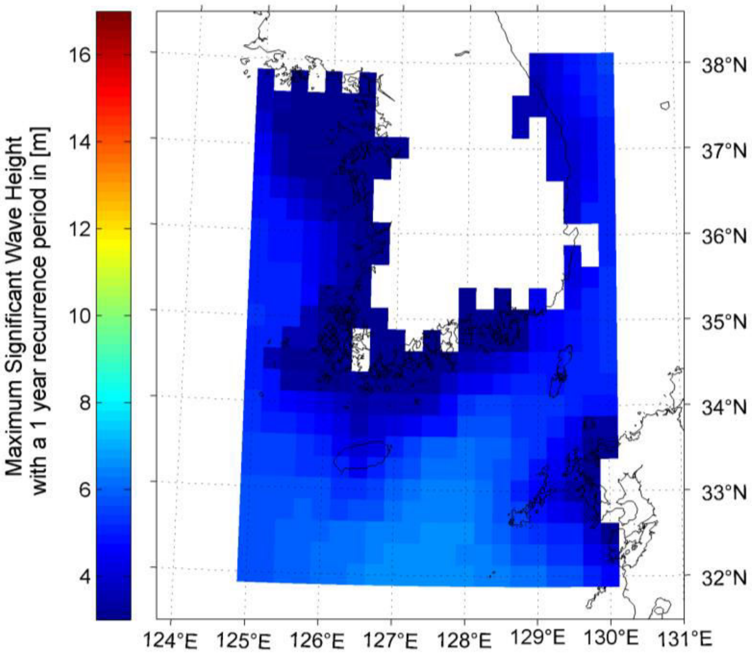

Figure C.29: Extreme significant wave heights with a recurrence period of 1 year in the target region *South Korea*

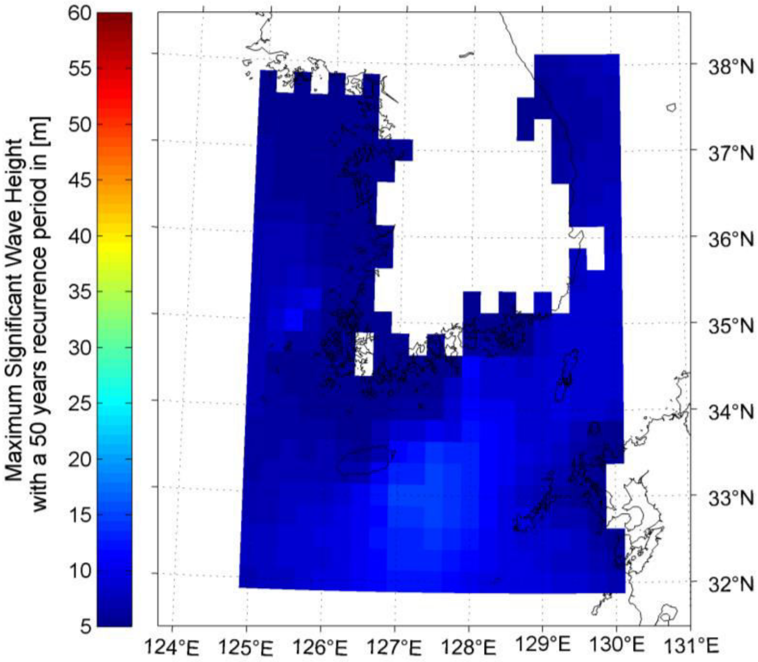

Figure C.30: Extreme significant wave heights with a recurrence period of 50 year in the target region *South Korea*

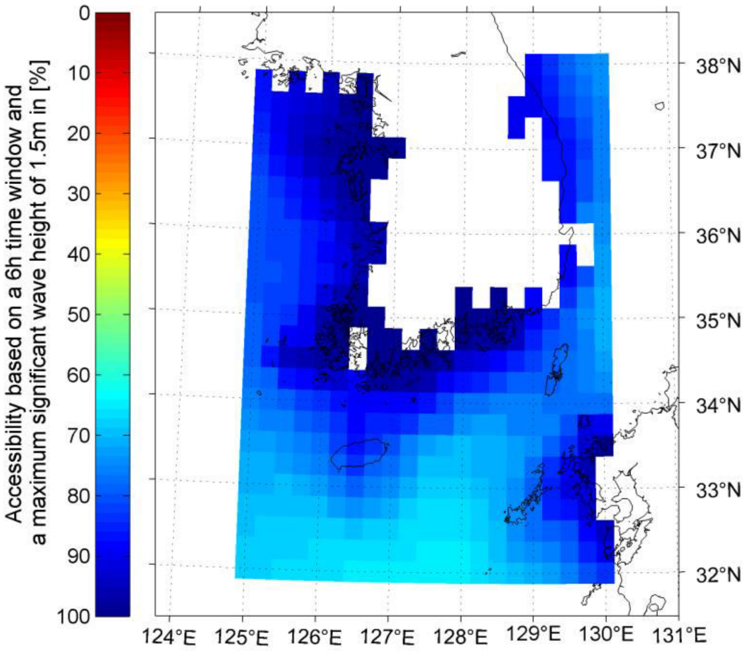

Figure C.31: Accessibilities based on a 6 h weather window (Hs≤1.5 m) in the target region *South Korea*

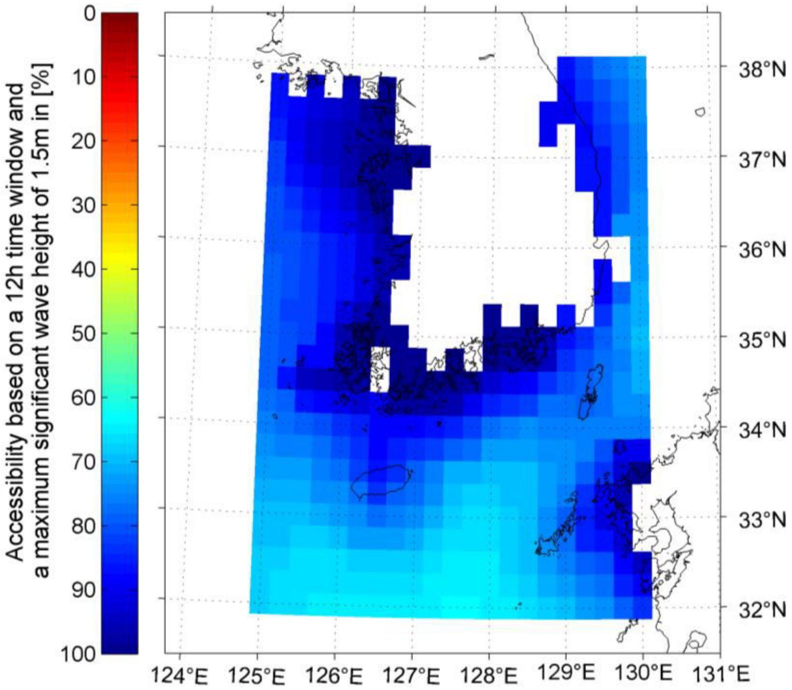

Figure C.32: Accessibilities based on a 12 h weather window (Hs≤1.5 m) in the target region *South Korea*

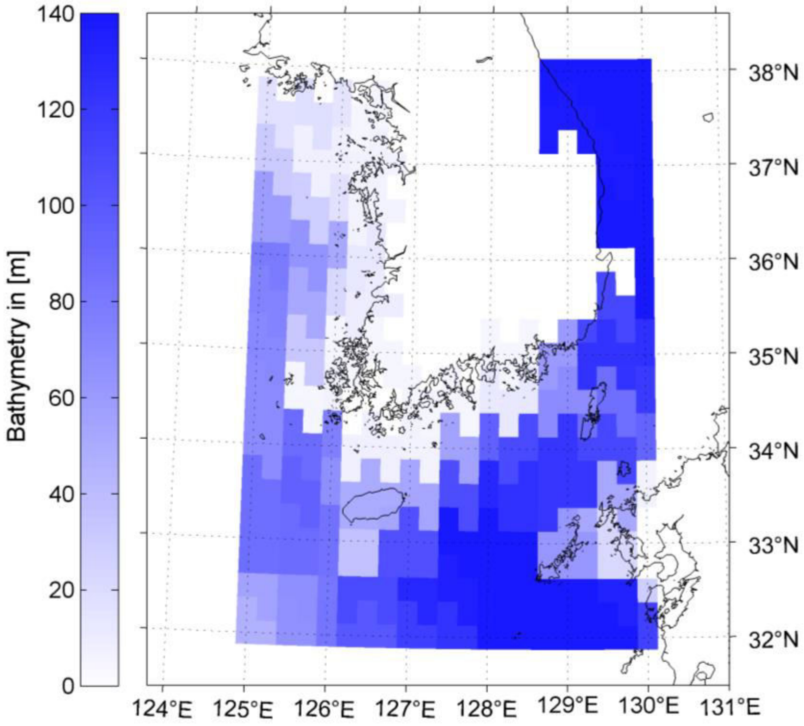

Figure C.33: Bathymetry in the target region *South Korea*

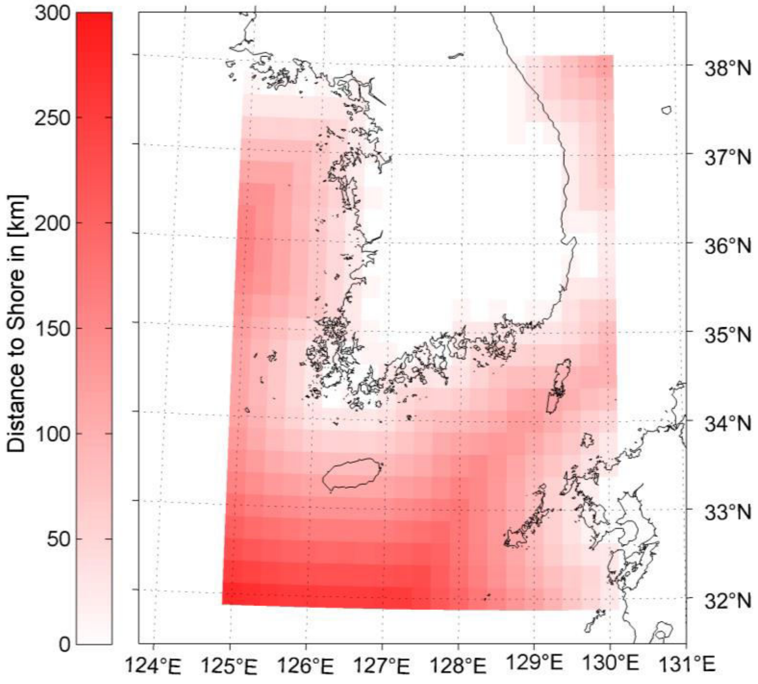

Figure C.34: Distance to shore in the target region *South Korea*

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Gemäß der Allgemeinen Prüfungs- und Studienordnung ist zusammen mit der Abschlussarbeit eine schriftliche Erklärung abzugeben, in der der Studierende bestätigt, dass die Abschlussarbeit „– bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit [(§ 18 Abs. 1 APSO-TI-BM bzw. § 21 Abs. 1 APSO-INGI)] – ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich zu machen.“

Quelle: § 16 Abs. 5 APSO-TI-BM bzw. § 15 Abs. 6 APSO-INGI

Dieses Blatt, mit der folgenden Erklärung, ist nach Fertigstellung der Abschlussarbeit durch den Studierenden auszufüllen und jeweils mit Originalunterschrift als letztes Blatt in das Prüfungsexemplar der Abschlussarbeit einzubinden.
Eine unrichtig abgegebene Erklärung kann -auch nachträglich- zur Ungültigkeit des Studienabschlusses führen.

Erklärung zur selbstständigen Bearbeitung der Arbeit

Hiermit versichere ich,

Name: Scheffler

Vorname: Ron

dass ich die vorliegende Masterarbeit bzw. bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit – mit dem Thema:

Development of a Methodology for Preliminary Site Assessment for Offshore Wind Applications based on ERA5 Reanalysis Data

ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

- die folgende Aussage ist bei Gruppenarbeiten auszufüllen und entfällt bei Einzelarbeiten -

Die Kennzeichnung der von mir erstellten und verantworteten Teile der Masterarbeit ist erfolgt durch:

- entfällt -

Ort	Datum	Unterschrift im Original
Hamburg	16.12.2019	