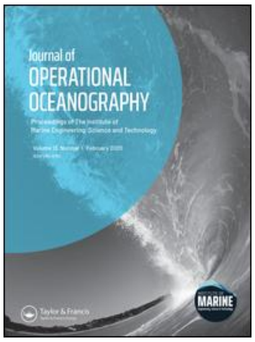

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Developing community marine data service for Blue Growth sectors

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ABSTRACT
Using Offshore Wind Farm (OWF) siting in the Baltic Sea as a demonstration case, key issues on developing community data services (CDS) for Blue Growth sectors are explored: e.g. data and product requirements, level of fitness-for-the-purpose and data gaps on the marine CDS for OWF. Through analysing the Blue Growth and marine service value chain as well as user requirements, a list of value-added products has been identified for two user groups: a public group for planning and managing the OWFs and OWF siting sector. Fit-for-the-purpose assessment is carried out to identify data adequacy for OWF siting per key variable in air, water, biota, seabed and human activity areas and per data characteristics, e.g. spatiotemporal coverage, resolution, timeliness, quality and accessibility. Major data gaps lie in observations of wind profiles, currents, sea ice thickness, bottom slope, sedimentation rate, grain size and transport. The results suggest that a community marine data service for OWF siting should be an integrated data portal with open and free data access. It should be a one-stop shop containing both raw data from satellite, in-situ, modelling, socio-economy and OWF sector, but more importantly tailored products which will allow performing feasibility siting on national scale.

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Community marine data service; blue economy; Baltic Sea; offshore wind farm siting; fit-for-the-purpose assessment

1. Introduction

The sea provides a large amount of resources for human benefits, in the areas such as fishery, aquaculture, coastal and maritime tourism, oil and gas, wind energy, navigation and marine mineral exploitation. In Europe, these economic activities in the sea are summarised under the term Blue Growth areas (DG-MARE 2012). Sustainable use of the marine resources helps to reduce the climate and human-related pressures on the marine environment. Therefore the Blue Growth activities are now managed by governmental agencies so that the impacts on the marine environment and ecosystem are limited and sustainable growth can be ensured. In Europe, a series of policies such as Water Framework Directive, Marine Strategy Framework Directive (MSFD), Marine Spatial Planning Directive (MSPD) and Common Fishery Policy, have been enforced in the member states so that the ecosystem-based management can be applied to make the Blue Growth activities more sustainable.

When implementing these common policies on national level, corresponding governmental agencies will need to make planning for all the Blue Growth activities in the country. On the regional level such planning is coordinated by regional conventions e.g. the Helsinki Commission (HELCOM, the Baltic Marine Environment Protection Commissions) in Baltic Sea and the Oslo Paris Commission (OSPARCOM) for the North Sea. All the Blue Growth sectors and corresponding activities will follow regulations made by national agencies and regional conventions. Figure 1 shows the value chain of Blue Growth. Governmental agencies, service providers and Blue Growth sectors have to work together. Detailed planning and management covers a large number of sectors and a significant amount of knowledge for both the sea and the Blue Growth sectors are needed. The national and international administrative agencies do not have sufficient expertise and resources to accomplish the task. Support will be given for the sea planning and management from the so-called service provider community, including, e.g. research communities, met-ocean operational agencies and consultancy companies. On the other hand, for Blue Growth sectors, in order to carry out operations at sea with safety and efficiency, they will need to know a wide range of information, from met-ocean forecast for operation planning, to climatological, geo-, bio- and habitat information for offshore operations. This will also be provided by the service community.

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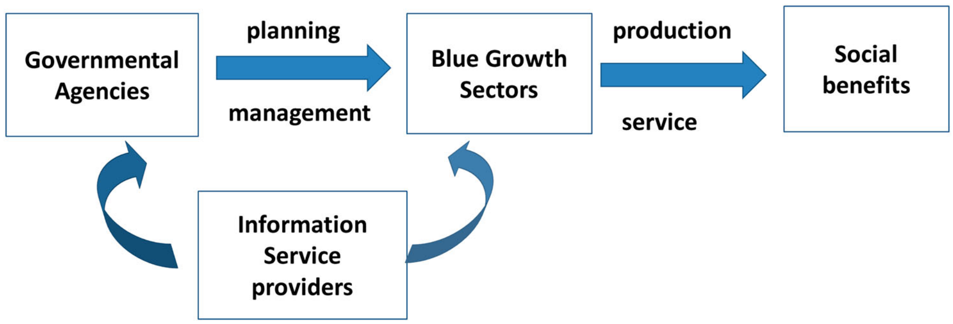

Figure 1. Schematic flowchart of the Blue Growth value chain.

In this paper, the marine service specifically refers to the service of providing necessary marine data, products and knowledge for decision-makers and industrial sectors to ensure that (i) the planned usage of the sea does not break the natural balance in the existing marine ecosystems, (ii) the exploitation of sea is safe and efficient and (iii) public and private users can access needed marine data and products. In Europe, significant efforts have been made for developing Community Data Service (CDS) on regional and European levels, e.g. Copernicus Marine Environment Monitoring Service (CMEMS, Le Traon et al. 2019) and European Marine Observation Data network (EMODnet, Míguez et al. 2019). This kind of service may significantly enhance efficiency of the decision-making procedure for planning and operation in areas of marine resources, coastal environment, maritime safety and weather and climate predictions (Bahurel et al. 2010).

The marine service value chain is illustrated in Figure 2. Through integrating observations with modelling tools, marine data and tailored products are provided by a public, open and free CDS to intermediate service providers, public sectors and sectorial end users. The CDS includes a core data service which provides different types of raw data and a tailored product service. Here 'tailored product' means a derived data or information product from observations and/or model data or other types of raw data, which can be easily understood and used by the users. The intermediate service providers, which can be either public or private, take data and tailored products from the CDS and further develop new value-added products to serve both public sectors and sectorial end users in order to meet more complicated user needs. This service is also called downstream service.

The CDS here is a general concept, including a 'core data service' and a 'core tailored product service'. The CDS is supported by public-good programmes on national, regional and European levels. Already today, a variety of marine CDSs have been developed in Europe (Table 1), e.g. European Marine Observation Data network (EMODnet), International Centre for Exploring the Seas (ICES). The core tailored product service is now still in its development phase. For example, Baltic Sea Operational Oceanography System (BOOS) provides tailored products of multi-model ensemble prediction products, water transport and algae bloom products. CMEMS provides a list of Ocean Monitoring Index. However, few tailored product service has been made for dedicated Blue Growth sectors. The existing marine

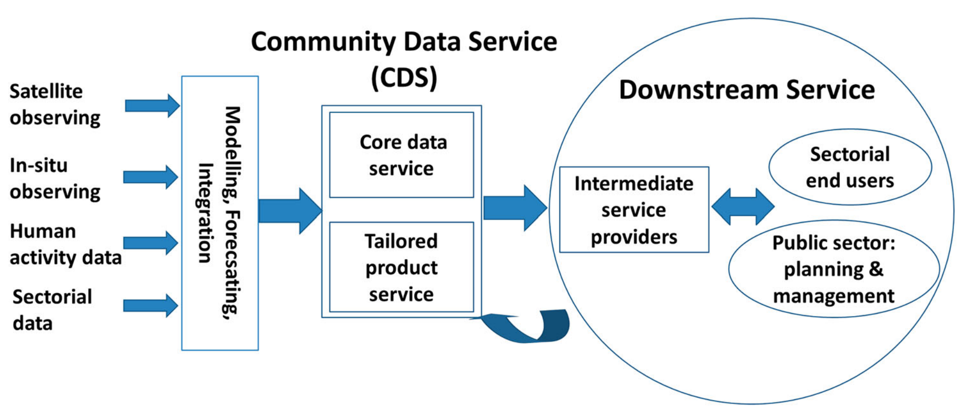

Figure 2. Schematic flow chart of marine service value chain.

Table 1. Some of the marine Community Data Service providers in Europe.

Data providers	Data type
CMEMS Monitoring and Forecasting Centres (MFCs)	Physical-chemical-low trophic level forecast and reanalysis
CMEMS Thematic Assembly Centres (TACs)	Satellite Sea Surface temperature (SST), sea ice, sea level, waves, winds, ocean colour
CMEMS In-Situ TAC	In-situ physical-chemical observations
European Marine Observation Data Network (EMODnet)	Air, water, biota, seabed, human activity, pollutants
International Centre for Exploring the Seas (ICES)	Water, biota, pollutants
Pan-European infrastructure for ocean and marine data management project (SeaDatanet)	Physical-biochemical observations
HELCOM	Water, biota, pollutants, seabed and human activity
C3S	Climate reanalysis, scenarios, reprocessed observations
Baltic Sea Hydrographic Committee (BSHC)	Bathymetry
National met-ocean agencies	Met-ocean, river discharge, air observations
National geological survey	Seabed, coastal zone
National environment institutes	Water, biota, seabed, pollutants
National fishery institutes	Water, biota, pollutants

CDSs are not dedicated for specific Blue Growth sectors. A fit-for-the-purpose CDS is yet to be developed.

In order to develop a marine CDS for Blue Growth sectors, two key issues need to be explored: the first issue is to identify requirements on the marine CDS in order to improve safety, efficiency and sustainability of Blue Growth activities; the second issue is to assess the fitness for the purpose of the existing CDS. Existing gaps are analysed and suggestions developed of how the CDS data gaps should be filled. In this paper, we use 'Offshore Wind Farm (OWF) siting' in the Baltic Sea as an example, to answers these questions. OWF siting is an industrial application that requires information of the wind energy condition, existing human activities, environmental conditions in the air, sea water and seabed as well as biota conditions. In Section 2, requirements on a marine CDS for OWF siting will be identified. Sections 3 and 4 analyse the existing CDS with regard to the second key issue, the fitness-for the purpose for OWF siting. Improvements to the existing CDS are suggested. For the two types of OWF siting, 'fit-for-the-purpose' means that existing data provided by the community data service are adequate for generating all the tailored products needed by both public agencies and private companies. Section 3 will define the correspondent tailored products, while Section 4 performs a detailed assessment of the data adequacy and identifies data gaps. Recommendations for how to fill the gaps are given in Section 5: conclusions and discussions.

2. Requirements on marine CDS for OWF siting

As show in Figure 2, users in the marine service value chain for Baltic Sea OWF siting can be divided into two groups: (i) governmental agencies responsible for marine spatial planning and energy planning and intergovernmental bodies in the Baltic Sea like HELCOM and the Vision And Strategies Around the Baltic sea initiative (VASAB), that set the development frame for offshore wind energy in their country and region and (ii) 'site developing' end users like energy companies and offshore marine architect and engineering companies that evaluate the detail potential of a site and define the development strategy for implementation (micro-siting).

Two types of OWF siting are concerned: one is the feasibility siting required by the governmental energy agencies and private firms; the other is the more comprehensive optimal siting required by wind energy companies. Initial feasibility siting acquired by the governmental agencies, is following a 'case-by-case' approach. In such a case, a tender for feasibility siting in one or more planned areas is first launched by the governmental agencies, then a competitive team (normally formed by a group of service providers) will get the bid and performs the siting. This procedure normally takes quite a long time, throughout which the relationship between the agencies and service providers is limited by the service contract. This can lead to a lack of overall design-and-feasibility coordination of OWFs on the national scale. By integrating all available data (e.g. in air, water, biota, seabed, human activity and OWF sector) and information products (e.g. wind power potential, topographic slope, sediment transport) for national and regional waters and providing them freely, a marine CDS provides a possibility for the governmental agencies to fulfil a nationwide OWF feasibility siting with less efforts and better quality.

More comprehensive optimal siting is needed for the OWF companies to estimate the potential cost–benefit performance of selected OWF candidates, which is directly linked to the economic return of the OWFs. Data with more localisation, higher resolution and wider parameter spectrum are needed. The task is normally performed by wind energy consultation companies which may not have sufficient knowledge on the community data availability due to lack of sufficient communication with the CDS providers. Hence it is important for the CDS developers to have direct communication with the wind energy consultation companies to learn their needs on the marine data and products for OWF siting.

In summary, a marine CDS for OWF siting should be a highly integrated service. Here 'integrated' means that all relevant data from air, sea water, biota, seabed, human activity and OWF sector should be collected and disseminated in a one-stop shop. Such a marine CDS for a target Blue Growth application (here OWF siting) needs to have both raw data service and tailored product service which serves user needs by integrating the raw data. Furthermore, the wind energy service providers will be able to combine the CDS data and products with their own data to generate more tailored products for OWF optimal siting. In section 2, tailored products for OWF siting by both the governmental users and industrial users are specified, which demonstrates the benefits of using marine CDS. Current European marine CDS (Table 1), such as CMEMS and EMODent are still too general to serve the Blue Growth sectorial needs. However, some CDSs, e.g. C3S, have already started to develop sectorial service.

3. Tailored product for OWF siting

In the Baltic Sea, there are about 201 wind farms which have been authorised, in operation, under construction or planned up to March 2018 (Figure 3). Figure 3 shows that all the European Baltic countries have planned a significant volume for offshore wind farm industry in the coming years, especially Poland and Sweden. According to the 4C-offshore database (4C-Offshore 2018), during 2010 – February 2015 the installed Baltic Sea OWFs have an averaged capacity of 198 MW. Assuming a Levelled Cost of Energy (LCOE, excluding system cost) of 61€/MWh (Lindroos et al. 2018) of the, a mean capacity of 200 MW per OWF and a capacity factor of 0.45 (Chabot 2014), the output of the power will be 158.5 TWh per year and the LCOE will be 9.67 BLN€ per year (excluding system cost). This means that any kind of optimisation of the OWF siting can be of significant savings in the wind farm industry, although this is just a rough estimation as there are uncertainties on future LCOE, OWF capacity and the capacity factor, especially studies have shown that the OWF factor has a rapid decline of the capacity factor in UK and Denmark from over 40% in year 0 and 1 to less than 15% in year 8–9 (Hughes 2012).

3.1. Tailored products for public agencies

For energy agencies, overall planning and design for OWFs is needed on the national level to ensure that the marine space is used in a cost-efficient and sustainable way. For a potential OWF site, public agencies not only consider its value in terms of wind strength and energy production, but also look at the layout of potential OWF areas to identify possible conflicts with socio-economic interests and national or international law: marine protected areas (MPA), Natura 2000 areas, marine spatial planning (MSP) and other regulations – marine traffic and ship routes, military relevant areas, dump sites for bombs, fishing, tourism, etc. To ensure the success of the general OWF site planning, it is essential to identify the right tailored products. Existing knowledge from previous service projects is used to identify a list of OWF siting service products for the public agencies:

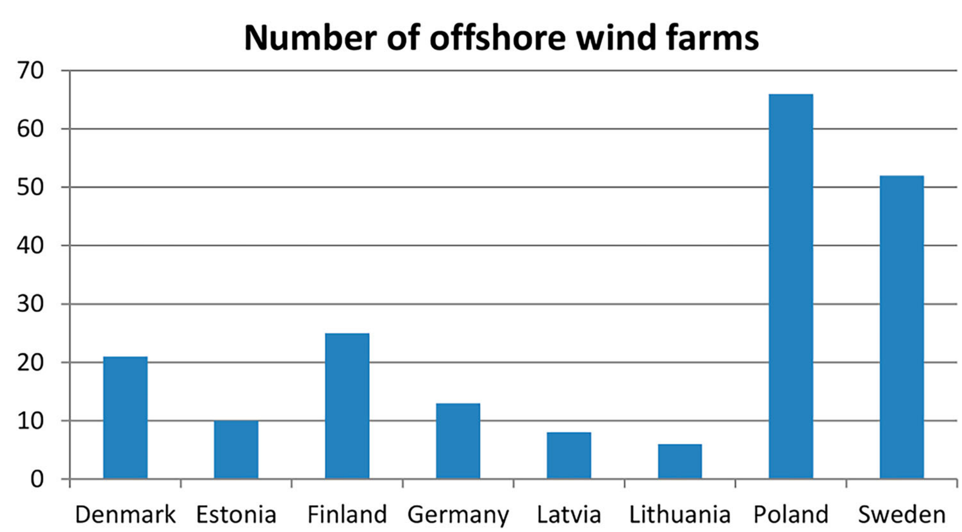

Figure 3. Total number of offshore wind farms (authorised, in operation, under construction and planned) per country in the Baltic Sea (data source: http://www.4coffshore.com/offshorewind/; Danish and German data are from EMODnet Human Activity http://www.emodnet-humanactivities.eu/view-data.php, 25 March 2018).

I. Areas with wind resources good for OWFs: this includes averaged wind resource maps in Baltic Sea marked with different categories at different height levels (50–260 m);
II. Areas with low environmental risks: the risks are represented by the intensity of extreme environmental conditions on winds, ice, waves and currents; return periods of 20, 50 and 100 years and 99 percentile of the key variables etc.;
III. Areas with low environmental and ecological confliction: maps of birds, fish spawning and marine mammals;
IV. Suitable geographical areas: map with isobaths of shallow waters, EEZ (Excluded Economic Zone), distance from the shore, existence of boulders and sediment morphology etc.;
V. Areas with low socioeconomic conflictions: maps of existing human use and activities according to critical levels;
VI. Areas matching existing electricity grids and wind farms: maps of sectorial information on the existing grid and wind farms and their capacity etc.

3.2. Tailored products for optimal siting by end users

Detailed optimal siting is needed to improve the cost-effectiveness of a selected OWF before it is constructed. This involves a number of assessments that rank in priority according to their impact on the cost–benefit analysis. The LCOE is the primary metric for describing and comparing the underlying economics of wind power projects. For wind power, the LCOE represents the sum of all costs of a fully operational wind power system that accumulates over the lifetime of the project with financial flows discounted to a common year. The principal components of the LCOE of wind power systems include capital costs (site acquisition and permitting costs, turbine cost, grid connection cost, foundation cost and installation cost), operation and maintenance costs and the expected annual energy production. Marine data are essential to the estimation of the grid connection cost, installation cost, maintenance cost and annual energy production. In addition, detailed technical configuration data on wind farms are needed.

Existing research showed that the LCOE is closely related to the water depth at the location of the wind farm and its distance from the shore. The cost of the mono-pile foundation increases exponentially with the water depth and the cost of the foundations increases linearly with the distance from the shore (Rosenauer 2014). The distance of an OWF from the shore affects the cost of electricity transmission in related to types of the foundation and transmission station used (Green et al. 2007). When an OWF is close to the shore, an alternating current (AC) substation can be installed at the OWF and connect to the electric grid on land via cables. With the distance increasing, there will be increasing amount of electricity loss in the cable. When the OWF is sufficiently far from the shore, an AC/DC (direct current) converter will have to be used in the OWFs to turn the generated power into DC first and then transmit the power through the cable in DC to the shore. This significantly reduces the electricity loss during the transmission in case of very long distance from the shore (Kirby et al. 2001; Negra et al. 2006). Finally, on land the DC power has to be transferred to AC before getting into the grid system. The cost of the AC/DC–AC transmission system is significantly larger than the AC solution about 15–25% of the total cost (S. B. Lauritsen, personal communication). Still, it is a cost-effective solution when OWFs are sufficiently far from the shore. In addition, by connecting several wind farms to the on-shore grid, the cost–benefit ratio on the transmission can be further improved.

Another large cost factor is the setting of the foundations during the construction phase of a bottom-fixed wind turbine and the installation of the piles. The cost is related to bathymetry, seabed slope, geology and hydro- and sediment dynamic near the sea bed. The average and extreme met-ocean conditions at the site, as well as the typical length and number of periods in which these conditions occur, are important for estimating the construction and maintenance cost, which can be quantified for certain vessel types and specific operations. It is necessary to provide additional information about typical weather windows with critical wind speed and wave height for certain operations, dependent on the type of operation and vessel at hand. Calm conditions are also required for a minimum period, e.g. 6 h for on-site operations and about 24 h for transport operations. More complicated operations would require additional information about fog, icing and eventual lightning, which have not been considered so far.

The economic benefit of a wind farm is its Annual Energy Production (AEP). Based on detailed, high-quality wind resource mapping data, optimal siting design can be made to identify potential wind farm sites which generate maximum AEP. Such analysis can be done for different types of wind turbines and foundations. AEP for a wind farm is determined mainly by the wind speed distribution at the location and the hub height, the swept rotor area and the efficiency of the wind turbine used (capacity factor). One of the main advantages of offshore wind power is its ability to obtain increased capacity factors compared to equivalent capacity onshore installations (Bach 2012; Hughes 2012). In the process of optimal siting, accessing to high resolution and high-quality wind resource mapping is one of the key issues.

Wind farm foundations are in direct contact with the sea and are affected by several physical and chemical processes. Sea ice pressure and the danger of colliding with drifting sea ice sets requirements for the strength and the type of the foundations. Near-seabed currents and sediment transport might uncover parts of the foundation or might lead to an exposure of the connecting cables, with costly consequences for the wind farm owner. On the other hand, salinity, i.e. salt-induced corrosion is an important factor when it comes to determine the life span of the foundations and piles. Only the maximum value of salinity near the seabed is used for the design studies.

Waves are important for operation support and the specification of suitable weather windows for both construction and maintenance operations. They might enhance the shear stress at seabed and contribute to the resuspension or even erosion of sediments at the site. Furthermore, they also add a wave component to the upwards mixing of smaller grain size fractions and therewith activate sediments for the horizontal redistribution by the currents. To estimate surface wave effects, the entire wave energy spectrum is to be considered.

Based on existing knowledge from the consultation projects for OWF end users in the Baltic Sea, a list of value-added products for industrial end users of OWFs is identified (in addition to the ones for the public end users – products I-VI) for addressing the above user needs:

VII. Probability Density Function (PDF) of winds: PDFs of winds and wind shear at different height levels up to 260 m
VIII. Seasonal variations of met-ocean parameter: monthly climatology for all met-ocean parameter
IX. Operation and maintenance working windows based on daily climatology
X. Near-Seabed currents
XI. Maximum salinity at seabed
XII. Area averaged wave spectrum
XIII. Near-seabed sedimentation rate and sediment transport
XIV. Seabed information: substrate type, lithology, stratigraphy, seabed slope

The above list of the tailored products for OWF optimal siting is not exhaustive. It should be noted that the tailored products are defined for marine CDS development only, which means that the list of products can be directly generated from the public core data service.

One example of value-added products for OWF siting is the spatial distribution of wind power potential which is important for both public and private users. Figure 4 shows the spatial distribution of mean wind power density at 100 m height (left) and the relative difference (in percentage, Figure 4 right), i.e. the difference between the mean wind power density at 100 and 190 m divided by the mean wind power density at 100 m. The results are estimated from the annual mean winds generated by a numerical weather model HIRLAM (High Resolution Local Area Modelling for numerical weather prediction) in a horizontal resolution of 3 km. As the water depth is an important indicator for the foundation cost, Figure 4 shows the 30 m isobaths as well. The fine-scale features shown in Figure 4 are very useful in OWF siting and cost–benefit analysis. The available wind resource at 100 m is higher in the southern Baltic Sea (Figure 4 left) where westerly winds are stronger and less shadowed by the land and mountain ranges of Norway and Sweden. This offers opportunities for wind energy investors in Denmark, Sweden, Germany, Poland, Lithuania, Latvia and Estonia. Especially high is the development potential in Poland and Lithuania and Latvia, where considerably high wind resource in shallow, near coastal waters exist. Germany, Denmark and Sweden have very suitable wind energy development sites as well, but these countries have already taken considerable steps to exploit their potential.

Shallower depths (<30 m) between the islands of Bornholm and Rügen have led to the initiation of a number of wind farm projects in Germany and Denmark. There are similar areas with shallower depth and suitable resource off the coast of Sweden and south of the Gotland. Although most of these areas are covered by Natura 2000 protected zones, it could be worthwhile to study these areas more in detail, to identify suitable sectors outside the protected zones.

In 2018 the rated power of a single wind turbine has reached 12 MW which has a tip height at 260 m and hub height at 153 m. Hence it is essential to consider the energy increase caused by the increase of hub/tip heights. Figure 4(b) shows that the wind power potential at 190 m is 10–100% higher than that at 100 m. The wind power increase with height is quite inhomogeneous in space. The relative increase of the wind power in the open waters is about 10%. However, the difference ratio quickly increases from offshore to coastal and estuary waters (20–100%) which is mainly due to increased bottom friction in the land side of the coast. This suggests that, in very shallow water areas, wind turbine

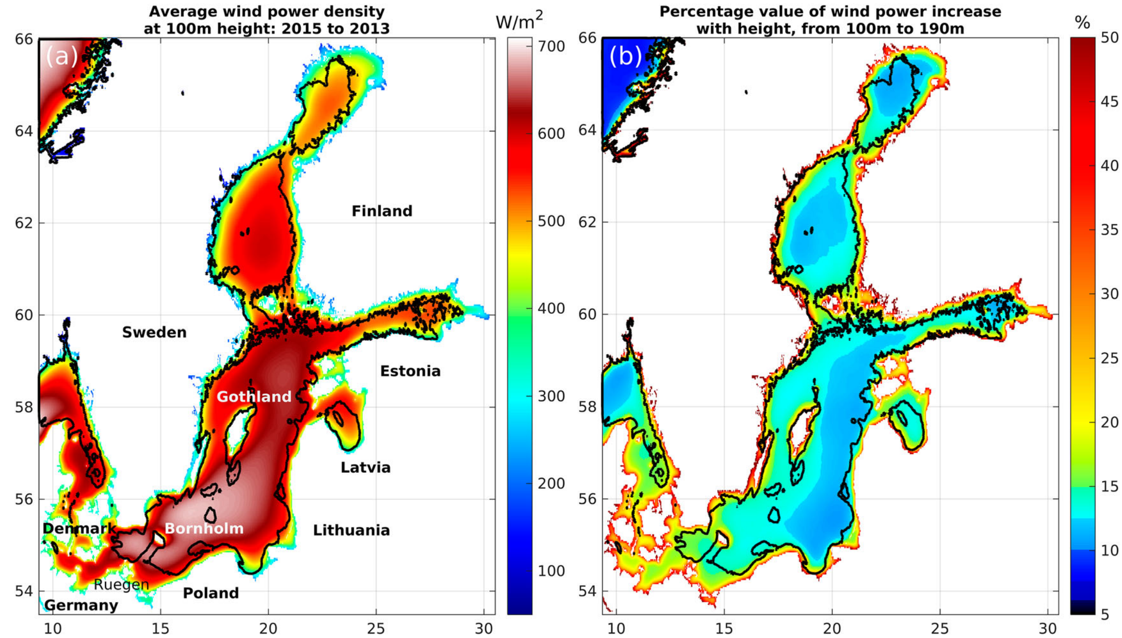

Figure 4. Average mean wind power density (a measure for the available resource) (left) and the relative difference (in percentage, right), i.e. the difference between the mean wind power density at 100 and 190 m divided by the mean wind power density at 100 m. The 30 m isobaths are shown as blackline.

with a higher hub height will have much larger wind power potential than the lower one. Using such kind of high-resolution information in Figure 4 for optimal OWF siting will allow developing optimal wind farm designs and may bring significant economic benefits.

4. Fitness-for-the-purpose assessment on marine data

After the core tailored products are identified, the fitness of the existing marine data for generating the tailored products can be assessed. This section assesses adequacy of the existing marine CDS for the purpose of OWF siting. Data gaps and significant bottlenecks in the existing marine data can then be identified and highlighted.

4.1. Methodology

There have been many EU projects aiming at assessing and optimising marine observational networks, e.g. EU FP5 project ODON (Optimal Design of Observational Networks), FP7 project OPEC (Operational Ecology) and JERICO (Towards a joint European research infrastructure network for coastal observatories). However, these projects mainly focused on the data requirements and quantitative impacts on operational oceanography. The questions that are answered in these projects are: how much can the forecast error be reduced due to the use and application of satellite and in-situ observations? What are the optimal sampling strategies for ocean forecast? This leads to observational network impact assessment, Observing System Experiment (OSE) and Observing System Simulation Experiment (OSSE) (She et al. 2007a; She 2018). The fitness-for-the-purpose assessment of the marine observations is more user-driven, integrated and qualitative comparing with above projects on assessing and optimising observing systems.

In this study, data adequacy is assessed per key variable and related characteristics, i.e. spatiotemporal coverage, resolution, quality, accessibility, completeness and appropriateness. Before the assessment, it is important to define terminology, glossary and evaluation criteria. The most important ones are described as follows:

- *Marine data*: all data, maps, tables and information describing status or change of marine atmosphere, sea and river waters, biota, sea bed and related human activities
- *Key variables*: the most important parameters needed in accomplishing the application tasks in a given challenge area. Many of them are already in the list of Essential Ocean Variables (EOVs)
- *Data characteristics:* characteristics of data to be assessed, e.g. coverage, resolution, quality, accessibility, completeness and usefulness
- *Data type*: the way that the data are produced, e.g. in-situ, satellite, model, integrated, publications, website and statistics
- *Data usage*: how the data are used in a given application area

- *Data requirements*: specification of the data characteristics based on the user needs
- *Data delivery*: referring to the entire procedure from data measuring to data access by the end users
- *Accessibility*: the level of data access in terms of
- *Delivery types*: how the data is delivered, including technical solutions e.g. web-based FTP (File Transfer Protocol) and post, timeline, e.g. online, near real time, offline, on-request and data policy applied, e.g. open, free, fee-based
- *Delivery time*: time interval between the data measuring time and the data accessible time (by the users)
- *Coverage*: the spatiotemporal or thematic coverage of the data
- *Completeness*: the percentage of the data that take account for the complete dataset in assigned data coverage
- *Resolution*: sampling interval in space and sampling frequency in time
- *Appropriateness*: describes how adequate given data characteristics fulfil the requirements for fitness-for-the-purpose
- *Precision*: deviation of the data from its true value and its scatter
- *Fitness-for-purpose data adequacy assessment*: for a given application area, to assess if the data are sufficient in their availability and accessibility in order to meet given purposes of the end users who use the data

The fitness-for-the-purpose assessment of the marine data adequacy for a given application area applies a qualitative method, including the following four steps:

1. To introduce the background of the challenge area, i.e. the purpose of using data, which key variable and data are used and how they are used, and to identify tailored products needed for the selected service;
2. To identify user requirements on the data characteristics for each key variable in order to generate the tailored products;
3. To identify existing characteristics for each key variable;
4. To assess data adequacy for each key variable to fit for the purpose of OWF siting by comparing the required and existing characteristics of the data characteristics.

The steps 1 and 2 are mainly based on opinions from the marine CDS providers, intermediate service providers, literature review and end users. The step 3 is based on an integration of information from the existing monitoring and data management centres, e.g. CMEMS, EMODnet, HELCOM and ICES, as well as national met-ocean agencies around the Baltic Sea.

For readability and clarity, the data adequacy for each assessment characteristics and key variable is assessed with three options: (i) data fit for the use (marked with 'FFU'); (ii) data are not adequate for the use; (iii) the adequacy of the data cannot be decided in the scope of the project. It should be noted that data may also include integrated products, e.g. outcomes of integrated use of the available data and models. In some cases, although in-situ marine observations are not adequate to fit the use of the applications, data products by integrating in-situ, satellite data and models are able to fit for the uses.

4.2. User requirements on data and products

The objective of the OWF siting is to identify feasible OWF sites with balanced economic, environmental and social impacts and consequences. This includes suitability analysis, impact assessment and optimal siting. The suitability analysis is a preliminary assessment that identifies locations which are suitable for offshore wind farms. This consists of wind condition suitability, met-ocean suitability and environment suitability. The impact assessment is to evaluate the environmental, ecological and social impacts of a given OWF site, i.e. impacts on the view, aquatic system and habitat. Optimal sites are characterised by the ratio of wind power production (benefit) to the cost of establishing and maintaining an OWF. The cost includes not only construction, deployment, transmission and maintenance cost, but also a cost due to negative environment, ecological and social impacts. The benefit also covers the economic (which is mainly through wind power generation) and positive impacts on the ecosystems and society.

One of the purposes of this paper is to provide an assessment on the marine data adequacy to fit for the use in OWF siting based on a practice of performing the feasibility siting in the Baltic Sea for selected sea areas. Since the average depth of the Baltic Sea is only 50 meters, a large part of the waters can be used for cheaper, bottom-fixed foundations. The key variables needed for OWF siting covers all 5 data matrix areas: air, water, biota, seabed and human activity (BSCP 2016). Data requirements are identified based on inputs from the core and intermediate service providers, e.g. met-ocean agencies, wind farm consulting companies, such as SWECO A/S as well as stakeholders, e.g. VASAB. The results are given in Table 2. Details of the data needs in terms of data characteristics are discussed in the following subsections.

Table 2. Data requirements for offshore wind farm siting.

Variable	Accessibility Delivery type & time	Coverage Spatio-temporal	Resolution Horizontal	Vertical	Temporal	Precision
Winds	Type: open, free; Time: months-years	Baltic Sea >10–20 yr.	Max. 5km	Surface + 5 heights up to 260 m.	Hourly-Monthly	Speed: <0.5 m/s Direction: 20°
Currents			Max. 1–2 km	<3 m at surface and seabed		Speed: 0.05 m/s Direction: 20°
Significant wave height			1–10 km	N/A		0.1–0.2 m
Wave period						1 s
Sea Ice			1 km	N/A		Concentration: 10%; Thickness: <45 cm; Drift: 40–80%
Birds, marine mammals etc.			N/A	N/A	Annually	N/A
Sea bed slope			50 m–1 NM	N/A	N/A	0.01 m/m
Seabed substrate			5 km	N/A	N/A	N/A
Sedimentation rate			5 km	N/A	Climato-logy	0.05 m/year
Bathymetry	Type: open, free Time: updated	Baltic Sea, most recent data	<50–500 m	N/A	N/A	0.5 m
Human activity: non-sectorial data			N/A	N/A	N/A	N/A
Human activities: sectorial data	Type: partly open, partly free; Time: updated		N/A	N/A	N/A	N/A

*N/A – Not Applied.

4.2.1. Weather and ocean data

Winds. Potential power of the wind grows with cube of the wind speed. Major advantages of the offshore wind farms are significant larger wind power outputs than the land-based ones (Hughes 2012), due to relatively lower roughness of the water surface and consequentially stronger winds. The roughness of the water surface is very low which leads to stable and relatively strong winds over sea, when compared with land surfaces. This gives higher and more stable wind power outputs. Such wind conditions over the sea are affected by the wave-induced roughness, current-induced surface drag and surrounding topography, e.g. islands and light-houses (Komen et al. 1994). Wind shear and wind gustiness are also useful parameters for the identification of optimum wind turbine design, as they reflect the vertical distribution and stability of the winds. Wind shade effects from land are important and can extend as far as 20 km out onto the sea. This requires wind profile data at more than one station. In recent years, due to wind turbine technology development, the large wind turbines need wind data up to 260 m above the surface.

In summary, wind data, especially those at the rotor height of the wind turbine (hub height), are essential in the OWF siting feasibility study. They are mainly used in estimating the potential wind resources available in the siting area and wind power production for different kinds of wind turbines, selecting turbine types and working windows (tailored products I, II, VII and IX). Historical gridded wind data are needed for a period longer than 10 years, a sufficiently high horizontal resolution (ranging from tens of metres to 2 km) and multiple vertical layers up to 260 m altitude. For 50–100-year return period estimation (extreme condition), preferably 20–30-year data in hourly resolution are needed. The data should cover waters shallower than 50 m. The quality of the wind data is high, especially small bias for mean value (<0.5 m/s) and PDFs. Observed wind profiles are needed for a minimum one year period at potential siting areas.

Ocean-sea ice-waves. For water variables, the most important variables for Baltic Sea OWF siting are sea ice (concentration, thickness and drift), waves (significant wave height, mean direction, dominant and mean periods, wave spectrum) and currents which have large impacts on calculating the loads on the foundation. Other variables such as temperature, salinity and chemical properties are needed in estimating the life span of the turbines and assessing environmental impacts of the wind farms. For the purpose of cable installation in very shallow waters, grounding and ridging information of ice is needed.

In summary, the ocean-ice-wave data are used to estimate both normal and extreme working conditions during the installation phase, as well as operation and maintenance conditions of the OWFs after deployment (tailored products II, VIII, IX, X, XI and XII). Historical gridded data are needed for a period longer than 10 years, a sufficiently high horizontal resolution (ranging from tens of metres to 2 km) at surface and bottom. For 50–100-year return period estimation, preferably 20–30-year data in hourly resolution are needed. The data should cover waters shallower than 50 m. In areas near the coast and islands, observed wind, wave and current data are needed while the model data should have spatial resolution higher than that in the open sea region in order to resolve sheltering, refraction and reflection effects caused by the complex topography.

4.2.2. Biota data

The detailed ecological impacts of the OWFs are closely related to the existing ecological status on the sites. The ecological impact assessment will need inputs from biota data, including the distribution of the high trophic level species (fish, birds and marine mammals), fauna, macro-algae and habitats. Existing research found that the offshore structures can create refuge areas for benthic species, adult and juvenile fish decreasing mortality that may result in positive effects for the high trophic level ecosystems and also economies through revenues from fisheries (Krone et al. 2013). As for the impacts of offshore wind farms on the seabirds, Cook et al. (2014) found that most gannets would avoid even entering a wind farm area, while gulls do enter the area but then avoid flying near the spinning blades. The study suggested that more than 99% of seabirds would change direction to avoid colliding with wind farms. However, the small proportion of flights that result in collision could still result in many thousands of birds being killed each year and could even significantly reduce the total populations of some species. It is therefore vital that individual developments avoid the most important places for seabirds. For marine mammals, challenge is in the installation phase, when piling has negative impacts on especially mammals (Bailey et al. 2014). Further research is also needed on the OWF impacts on the marine mammals due to increased underwater noise level.

In summary, high trophic level biota data (Baltic fish closure, wintering areas of birds especially for endangered ones and marine mammal abundance) are needed for estimating the ecological impact of the OWFs (tailored product III).

4.2.3. Seabed data

Seabed characteristics, including not only bathymetry, substrate types but also slopes, seismic structures, sedimentation rate and transport are important for designing and installing the OWF foundations (tailored products XIII and XIV). Seabed sediment and substrate affect the construction cost of the OWFs. A good site should have stable sediments that are difficult to mobilise and are not easily redistributed. While the construction of the underwater foundation is underway, the existing habitat in the seabed will change and might even be degraded or destroyed. Assessment of OWF construction impacts requires the collection and provision of habitat data.

Sediment transport data are needed during the design of cable installations, especially in shallow waters. Since the cables are normally installed 1.5–3.5 m below the seabed (S. B. Lauritsen, personal communication), significant sediment transport may remove the upper sediment layer (e.g. coarse sands) exposes the cable and makes them vulnerable to fish trawling activity. The repair of the cable damage may take up to 3–4 months.

Bathymetry and seabed slope: topography and distance to the shore/harbour are among the most important factors to determine the investment cost of the OWFs. Detailed bathymetry and seabed slope data (with horizontal resolution of 1 m) are needed for optimal siting. For feasibility siting, a horizontal resolution in a few hundred metres is required.

4.2.4. Human activity and sectorial data

The impact of the OWFs on coastal areas varies across a number of thematic dimensions. Positive impacts include their contributions to a diversified and cleaner electricity supply that reduce greenhouse gas emissions and open up job opportunities for supporting manufactures of wind turbine components. The feasible waters for OWF development, however, may already have been employed for other uses, such as for shipping lanes, marine protected areas, cultural resources like shipwrecks, commercial fishing areas, and military operation areas. To assess the pros and cons of a potential OWF program (tailored product V), a database of existing human activities in the Baltic Sea is needed. It is important that such a database should be updated to reflect most recent and even on-planning activities.

Sectorial data on the OWF industry are also required for estimating the potential cost of the OWFs such as costs of OWF foundations, installation, transmission centre and electricity grid information (tailored product VI). Some of these data may not be freely available or might be expensive or difficult to obtain from the OWF companies and/or local governmental agencies.

4.3. Existing characteristics of data and adequacy assessment

In this study, data adequacy is mainly assessed for the purpose of identifying suitable sites for wind farm development. Aspects of ecological impact assessments and cost-effective siting are only touched upon, without further investigating them in depth. Firstly the characteristics of the existing data are presented and then the adequacy is assessed against data requirement for each key variable and assessment criterion, i.e. data characteristics. The characteristics of the existing data are summarised in Table 3 while the assessment results of the data adequacy are summarised in Table 4.

Table 3. Characteristics of the existing data for offshore wind farm siting.

Variable	Data type Sources	Accessibility	Coverage Spatiotemporal	Resolution Hor./Ver./Temp.	Precision
Wind profiles	In-situ (private, public)	Restricted, on request,	Baltic, 1960-	Up to 200 stations/a few heights up to 130 m/hourly	0.1 m/s
	Model (C3S*, Met. Agencies)	On request or open, free	Baltic, 1980-	3–11 km grid/user specified levels/hourly	1–1.5 m/s
Winds at 10 m	In-situ (BOOS, GTS*)	Open, free or on request	Baltic, 1900-	Sparse points/hourly	0.1 m/s
	Satellite (CMEMS, ESA*)		Baltic, 1993-	1–25 km grid/ varying temporal	1 m/s
Currents	In-situ (BOOS, EMODnet)		Baltic, 1990-	16 stations/1–2 m/ hourly	<0.1 m/s
	Model (CMEMS)		Baltic, 1989–2016	1–3.5 km/Multi-layers/hourly	0.1 m/s
Waves	In-situ (BOOS, EMODnet)		Baltic, 1990-	22 stations, hourly	Hs: 0.01 m; Period: 0.1 s
	Satellite (CMEMS)		Baltic, 1993-	>7 km along track, instant	Hs: <0.1 m
	Model (CMEMS, Met. Agencies)		Baltic Sea, 6–40y	1–10 km, hourly	Hs:0.3–0.5 m; Tp: 1–3 s
Sea Ice:	Satellite (CMEMS, FMI)	open, free	Baltic, 1979-	1–3 km, daily	Concentration: 10% Thickness: <45 cm
	Model (CMEMS)		Baltic, 1989-	2–6 km, hourly	
Birds, marine mammals	In-situ (HELCOM, EMODnet)	On request or open, free	Baltic, most recent data	N/A	N/A
Bathymetry	BSBD, EMODnet	Open, free	Baltic, updated	250–500 m	∼10°m
	National data	Restricted	Baltic, except for Russia and Lithuania	<50–100 m	1 m
Seabed habitat	In-situ/model mixed, EMODnet	Open, free	Baltic, updated	1: 250,000	N/A
sedimentation rate	In-situ, EMODnet		Baltic Sea with gaps	Sparse stations	N/A
seabed slope	In-situ, HELCOM		Baltic, static	N/A	0.01 m/m
Human activities	Public data, HELCOM, EMODnet		Baltic, updated	N/A	N/A

*C3S: Copernicus Climate Change Service; GTS: Global Telecommunication System; ESA: European Space Agency; N/A: Not available.

4.3.1. Wind conditions

In order to meet the user needs on wind data, an integrated approach is needed, that includes different technologies from in-situ observing (e.g. wind masts and buoys), remote sensing (e.g. Light Detection and Ranging – LiDAR, Synthetic Aperture Radar – SAR and Scatterometers) and numerical modelling. High-quality in-situ observations are spatially sparse but temporally dense and can be used in validating and calibrating the remote sensing algorithms and numerical models; spatially wide remote sensing data can be assimilated into numerical models to generate long-term reanalysis with high resolution and quality.

Sea Surface Wind (SSW) observations. The SSW at 10 m height is monitored through both satellites and in-situ platforms. The satellite SSW vectors are mainly

Table 4. Data adequacy assessment for offshore wind farm siting.

Variable	Data type	Accessibility	Completeness/ coverage Spatial/Temporal	Resolution Hor./Ver./Temp.	Precision
Wind profiles	In-situ	Existing data should be more open	More new data are needed. Time series over sea are sparse and too short on hub height (100–150 m) Lack of offshore wind profile measurements		
	Model	More user friendly data extraction	Data are adequate for extreme estimation up to 50 yr–100 yr return periods. Reanalysis needs higher spatial resolution (3 km)		
Currents, salinity	In-situ	More national data should be open.	More currents observations are needed.		
Currents, salinity	Model	FFU	FFU		
Waves	All types	FFU	FFU		
Sea Ice	Model, satellite	FFU for ice concentration.	Ice charts go back a longer time, but not digitalised before 2009. Model data have adequate coverage and resolution but needs more validation and quality improvement		
Birds/marine	In-situ	FFU	FFU for site suitability but not adequate for ecological impact assessment		
Bathymetry	In-situ based + model	FFU for feasibility study but not adequate for Russian and Lithuanian waters and some shallower waters, and for micro-siting.			
Seabed substrate		FFU for feasibility study but not adequate for micro-siting.			
Sedimentation rate		Not adequate			
Sediment transport		Not adequate			
Seabed slope		FFU for feasibility study but not adequate for micro-siting.			
Human activities	statistics	FFU for feasibility study; more sectorial data are needed for micro-siting			

measured by SAR and scatterometers. SAR provides very high resolution (in 500–1000 m grid) winds but with limited coverage. Since 2002, ENVISAT ASAR and Sentinel-1 A/B SAR are in operations. A full Baltic Sea coverage of SAR data provides 600–1200 samples per pixel (Hasager et al. 2011). This dataset has been used to generate wind resource estimation in NEWA (New European Wind Atlas) project. The scatterometer has spatial resolution in 12.5 km and 25 km and repeat cycle of 29 days. Special Sensor Microwave Imager (SSM/I) provides wind speed products in 25 km resolution with daily global coverage. The satellite wind data are sufficiently accurate to generate wind climatology. These data are quality controlled, reprocessed and are freely available through major data portals of CMEMS, CERSAT (Centre ERS d'Archivage et de Traitement) and Jet Propulsion Laboratory (JPL). Examples are JPL CCMP (Cross-Calibrated Multi-Platform) Level 4 SSW product for period of 1987-7-2 to 2011-12-31, in 6 hourly and 0.25×0.25 degree resolution, CMEMS Level 3 SSW daily-instantaneous product for the period of 1992-3-2 to present, in 0.125×0.125 degree resolution. The in-situ offshore SSW is measured by Voluntary Observation Ships, buoys and ferry lines, which are available from met-ocean agencies and data portals of BOOS, CMEMS and EMODnet. The historical and near real-time SSW data well cover the Baltic Sea coast, which can be obtained from European Climate Assessment Dataset.

Wind profile observations. Accurate measurement of wind profiles aloft in the marine boundary layer is expensive and observations are sparse. Furthermore, temporal and spatial behaviour of near-surface winds is often unrepresentative of that at the required heights. In Baltic-North Sea transition waters, offshore wind profile data at 17 locations are collected (Hasager et al. 2011). The data is mainly owned by wind farm companies and limited for open access. A widely used data source for in-situ wind profiles is from the FINO-2 meteorological mast which is the second of the three German 'Forschungs-plattformen in Nord- und Ostsee' (research platforms in the North and Baltic Seas). It is located midway between Germany and Sweden, around 38.2 km and 38.6 km, respectively. The wind speed is available at 32, 42, 52, 62, 72, 82, 92, 102 m height.

In recent years, LiDAR devices have been more and more used to make the wind profile measurements. In the Baltic Sea, however, there rarely are openly (or freely) available offshore wind LiDAR data. It was reported that a few wind LiDAR stations have been maintained in Finnish and Latvian coasts and islands. Long term measurements are available and have been used in wind power and meteorological studies (Vakkari et al. 2015; Bezrukovs et al. 2015). Recently it was reported that a type of ZephIR 300 M floating wind LiDAR will be deployed in Polish Baltic waters for the design of a 1GW offshore wind farm that has been planned for the area. It is noted that the quality of the LiDAR measurements should be further improved. The current practice is to calibration the LiDAR data to the profile data from the meteorological masts.

It is expected that the overall availability of the wind profile observations will largely increase especially due to increase of the planned OWFs (Figure 3). In each OWF, at least one-year wind profile observations will have to be measured. However, these data may not be accessible. Therefore major problem is not a lack of observations rather than data accessibility.

Wind data from models. Major part of the three-dimensional (3D) winds and other meteorological data for wind farm siting are provided by the Numerical Weather Prediction (NWP) models, normally needed for a period longer than 10 years. Several global reanalysis products are available for the past 40 years or longer: ERA-Interim, NCEP CFSR and more recently ERA5, but spatial resolution are too coarse (30 km or coarser). Regional high resolution (in 3–5 km grid) analysis and 6 h forecasts starting from 2003 are available from DMI. Hindcast downscaling from ERA-Interim has 5 km resolution for 1979 onwards (CORDEX). Regional reanalysis has a resolution of 5–11 km by downscaling from ERA-Interim (1979-) from EU projects EU4M and UERRA (Bach et al. 2016). A new C3S European reanalysis will be generated by downscaling from ERA5 based on a regional NWP system HARMONI-3DVAR in 5 km resolution.

Adequacy assessment. The existing observing, modelling and data integration technologies on wind conditions are fit for the purpose of OWF siting. By comparing the existing wind data characteristics with the required ones in Table 2, it is found that one of the major wind data gaps is the lack of accessibility of wind profile observations. In addition, the quality of LiDAR winds needs improvements. Both the resolution and quality of long-term wind reanalysis products should also be improved.

4.3.2. Water conditions

Water conditions in the marine boundary layer such as sea ice, currents and waves affect the winds, turbulence and the loads on the turbines. For wind farm siting study, high-resolution and quality data product are needed, which can only be obtained by integrating in-situ and satellite observations with models.

Sea ice observations. Ice data (ice edge, concentration, thickness and drift) can be obtained from satellites.

CMEMS provides sea ice edge and concentration data in a 0.03 degree resolution since 1982 based on a blending of multiple satellite products, and ice thickness and drift data with high spatial resolution (0.5 km) based on SAR products since 2009. Older sea ice data based on SAR is available, e.g. from the Finish Meteorological Institute, but has not been digitalised yet.

Current observations. In EMODnet Physics, there are 16 moorings (including historical ones) that are measuring currents in the Baltic Sea for different periods in the last 10 years. These are mainly located in the Kattegat, southern and western Baltic Sea and Gulf of Finland. The observations have been mainly provided by BOOS members. No data is found in the eastern Baltic Sea and northern Baltic Sea. In fact, there are national monitoring programmes in Estonia and Finland providing current measurements in these areas.

Wave observations. In EMODnet Physics, there are 22 mooring buoys (including historical ones) measuring waves in the Baltic Sea for the past 10 years, distributed in the entire Baltic Sea. In addition, satellites provide high-quality measurements from altimetry in a resolution of 7–20 km. The aggregated products for a period more than 20 years are downloadable from CERSAT website. In the coming years, CFOSAT (China-French Oceanography Satellite) will provide wave spectrum with swath coverage in 70 m resolution.

Water data from models. Several state-of-the-art ocean-ice-wave-biogeochemical models have been developed and applied to generate decadal hindcast and reanalysis time series for the Baltic Sea. The ocean-ice hindcast and reanalysis data are mainly derived by using HBM (HIROMB-BOOS Model) and NEMO (Nucleus for European Modelling of the Ocean)-Nordic models with assimilating SST, water temperature and salinity (T/S) profiles and/or sea ice concentration (Fu et al. 2012; Liu et al. 2017). CMEMS currently provides ocean-ice reanalyse in 2 nautical mile (nm) horizontal resolution for the period of 1989–2016 based on NEMO-Nordic. A 13-year hindcast of ocean-ice conditions for the Baltic Sea in horizontal resolution of 1 NM for the Baltic Sea and 0.5 NM for the Baltic-North Sea transition waters was produced by DMI and used in Danish wind farm siting projects.

Several versions of the wave climate of the Baltic Sea are reconstructed based on wave model WAM. For example, a 52-year hindcast (1957–2008) in 3 NM horizontal resolution was produced by Nikolkina et al. (2014). However, the effect of sea ice cover was not included. A 6-year wave hindcast in 6 NM resolution was produced by FMI, including sea ice conditions (Tuomi et al. 2014). The wind forcing used in the hindcast was FMI-HIRLAM analysis/forecast with varying resolutions (9–22 km). A 13-year wave hindcast in 6 NM resolution was produced by DMI with HIRLAM analysis/forecast in 3–5 km resolutions as forcing and sea ice included. It provides boundary conditions for a 1 NM resolution hindcast covering the Baltic-North Sea transition waters (7-16E, 53-60N). Wave hind-cast results in 1 NM resolution have been used in Danish offshore wind farm siting projects. In the coming years, a decadal wave hindcast product in 1 NM resolution for the entire Baltic has been planned in CMEMS BAL MFC (Baltic Marine Monitoring and Forecasting Centre).

Adequacy assessment. Observations of historic sea ice conditions have sufficient spatial coverage. Temporal coverage is adequate for ice concentration and ice edge but not for ice thickness and ice drift. Long-term sea ice data can be obtained from ocean and sea ice models but the ice thickness and ice drift products have not been well calibrated. Sea ice grounding and ridging data is not adequate either from observations or models. Wave models are well calibrated in Baltic Sea and can generate wave products in adequate resolution and quality for the OWF siting, although further improvements needs to be made on island-caused sub-grid impacts, current-wave interaction and ice-wave interaction. Currents information in the Baltic Sea for OWF siting mainly relies on models. It is a challenging task to generate high-quality currents both in surface and bottom. More in-situ observations are needed. To resolve water exchange in narrow Danish Straits and complex bottom topography, high resolution and flexible grid are needed to resolve narrow Danish Straits (She et al. 2007b).

4.3.3. Biota conditions

The biota data are mainly used in impact assessment of the OWFs, to generate tailored product III. Major concerns are impacts of OWF on birds and marine mammals in the Baltic Sea.

Birds. A major data source on birds is from HELCOM, e.g. important bird areas and wintering bird areas can be found in HELCOM Data and Map Service (DMS). There are only two datasets for birds available in EMODnet Biology: one is the Baltic seabirds transect survey in the central Baltic Sea, the other is JNCC (Joint Nature Conservation Committee) seabird distribution and abundance data from ESAS (European Seabirds At Sea) database, mainly in Kattegat and Skagerrak. The bird areas are mostly found in shallow water areas, which overlap with existing and potential wind farm areas. Although the existing research showed that 99% of the birds can avoid wind farms (Cook et al. 2014), there still can be enhanced risks for certain species due to the presence of wind turbines.

Marine mammals. As discussed in section 3, the installation of wind farms can have some negative impacts on marine mammals. A comprehensive marine mammal dataset is needed, that includes data from all available sources. HELCOM has the following datasets:

– The HELCOM Red list datasets: showing red-listed species by the stage of becoming extinct in five species groups (macrophytes, benthic invertebrates, birds, fish, and marine mammals). The sixth group includes biotopes also classified by the stage of becoming extinct. In addition, biotope annexes show ten biotope combinations that are in danger of becoming extinct in the Baltic Sea. Spatial data on occurrence can be accessed from the Biodiversity map service.
– HELCOM Harbour porpoise database contains information on sightings, by-catches and stranding of harbour porpoises in the Baltic Sea. The Biodiversity map service displays the reported data on harbour porpoise inside the HELCOM marine area.
– HELCOM Seal abundance dataset, showing spatiotemporal distribution of the Baltic seals.

No marine mammal data were found in EMODnet for the Baltic Sea.

Adequacy assessment. Existing biota data fit for the purpose of the Baltic Sea OWF siting.

4.3.4. Seabed conditions

The EMODnet Seabed Habitat website provides a permanent single portal for accessing seabed habitat data in Europe. This includes the EMODnet broad-scale seabed habitat map for Europe and habitat maps from surveys across Europe. The EUSeaMap is currently available to end users at 250 m resolution. This map will aim to be available to end users at a scale of 1:100,000 or better, depending on the resolution of the input data layers. The habitats are classified according to the EUNIS (European Nature Information System, Version 2007-11) habitats classification, and also as MSFD 'Benthic Broad Habitat Types'.

EMODnet Geology provides data on seabed substrate, sedimentation rate, seabed lithology and stratigraphy.

Seabed substrate. General information and data of seabed conditions can be found in EMODnet Geology and HELCOM-DMS, e.g. types of substrate in polygon. EMODnet Geology provides seabed substrate data at scales of 1:250.000 and 1:1.000.000, respectively. The 1:1.000.000 map is collated from the 1:1M data and generalised 1:250k EMODnet data. Where necessary, the existing seabed substrate classifications (of individual maps) have been translated to a scheme that is supported by EUNIS. This EMODnet reclassification scheme includes at least five seabed substrate classes: mud to sandy mud, sand, coarse and mixed sediment, as well as rock and boulders as an additional substrate class. The original data set has been mode detailed. However, the original 16 classifications have been summarised into the 7 classifications that are presented here. The data from EMODnet Geology have some data discontinuities. The gaps are filled with model data in EMODnet Seabed Habitat.

Bathymetry and seabed slope. The best public available bathymetry can be obtained from BSHC (The Baltic Sea Hydrographic Commission) and EMODnet, which are basically the same. The BSHC has produced a Baltic Sea Bathymetry Database (BSBD) based national contribution of gridded bathymetry data from 50–500 m resolution covering their EEZ and territorial waters. For Russian and Lithuanian waters, GEBCO_08 (General Bathymetric Chart of the Ocean) 1-min resolution data were used. The newest version is v09.3. The BSBD website provides a dynamic 'position – depth' service. EMODnet Bathymetry combines BSBD newest version topography model and new data from other resources, providing a dataset of 250 m resolution. For siting suitability study for a typical wind farm in a diameter of a few kilometres, the EMODnet data should be sufficient to provide a baseline reference except for Russian and Lithuanian waters and some shallow water areas with low sampling rate. The seabed slope data are a product from BALANCE (Baltic Sea Management – Nature Conservation and Sustainable Development) project.

Sediment transport and sedimentation rate. The seabed sedimentation rate data can be found in EMODnet Geology. Estimations of modern sedimentation rates (cm/year) are based mainly on the 137Cs and the 210Pb dating. The 137Cs could be used as a time-marker in the sediment column. In the sediment column, the activity peak of 137Cs corresponds to the fallout of the Chernobyl nuclear power plant accident of April 1986. Some sedimentation rates were estimated from acoustic-seismic and sediment core data. There exist large spatial and temporal gaps in the sedimentation rate data. There are few measurements of the sediment transport, especially for transportation of coarse sand.

Adequacy assessment. for the purpose of OWF feasibility study, major seabed data gaps lie in the quality of bathymetry in Russian and Lithuanian waters (due to lack of accessibility) and some shallow water areas (due to lack of observations), sediment grain size, sediment transport and sedimentation rate data. The more detailed data, if needed, will have to be obtained through on-spot measurements for optimal siting.

4.3.5. Human activities and sectorial data

The human activity data in the Baltic Sea can be obtained from web portals of HELCOM-DMS and EMODnet Human Activity Thematic Portal. In general, HELCOM-DMS contains more human activity data than the EMODnet portal. Relevant human activity data such as shipping lanes, marine protected areas (areas of Natura 2000, United Nation heritage and national protected areas), dredging and deposition areas, chemical weapon dumping areas, cables, pipelines, landing station, existing and planning wind farms, offshore oil exploration areas, bird and marine mammal and commercial fishing areas as well as coastal defence areas are given in the HELCOM-DMS.

Some human activity data is not available from either HELCOM-DMS or EMODnet, e.g. electricity grid network in the Baltic Sea and regulatory documents which are in general hold by national agencies. Such information, however, can be easily found from public resources. Thus in general the human activity data for the OWF site feasibility assessment in the Baltic Sea is considered as adequate.

Sectorial data, e.g. general information on the existing and planned OWFs, characteristics and costs of different types of wind turbines and foundations and transmission stations are needed for cost–benefit analysis. Some of the information is publically available through HELCOM, EMODnet Human Activity and 4C-Offshore global OWF database. Many of cost-related data, however, are mostly hold by the private sectors and may not be available for public access.

5. Conclusions and discussions

In this paper, a few key issues related to the development of a marine CDS for Blue Growth sectors are investigated: requirements on the marine CDS for Blue Growth sectors, (ii) to which extent the CDS data fit for the purposes and (iii) where the data gaps are and how they can be filled. These issues are important not only for end users who use the CDS but also for CDS developers. Methodology for fit-for-the-purpose assessment of marine data is developed and demonstrated by identifying user needs on data and tailored products, investigating availability and accessibility of marine data and assess data adequacy for OWF siting in the Baltic Sea.

The results show that, in order to fit for the purpose of OWF siting, the CDS should be able to collect, integrate and disseminate multi-disciplinary data from air, water, biota, seabed, human activity and OWF sector. The raw data can be produced through remote sensing, in-situ monitoring, modelling or socioeconomic statistics. In addition, integration of different types of data, e.g. from remote sensing, in-situ and modelling data can extend data coverage, hence to fill the existing data gaps. It should be noted that the OWF raw data service only needs to collect raw datasets relevant to OWF industry. Besides the raw data service, the OWF community data service should also provide a tailored product service for both public and private OWF related users. Design of the tailored products based on requirements from both public and private users is a pre-requisite condition for the fit-for-the-purpose assessment.

Tailored products and integrated data usage make OWF siting feasible on national and regional scale. This can improve cost-effectiveness of wind farm planning by public agencies. There also exists huge potential to make significant economic benefits by doing detailed OWF optimal siting using high-resolution wind power potential maps.

Data availability, accessibility and appropriateness are investigated for all key variables. The adequacy of the data is assessed through generating needed tailored products. The results are useful for both, public service providers to improve the marine CDS and for private users to get an overview on what data are available and accessible.

Wind profile data is most important for OWF siting. The results show that there is a lack of wind profile measurements. It is recommended that wind profile data, from either public or private owned providers should be more open for research purposes, e.g. to calibrate operational Numerical Weather Prediction models. More wind profiles should be measured by using existing cost-effective technology, such as ship-born, fixed or floating platform-based Doppler LiDAR. Wind data from reanalysis have sufficient horizontal and vertical resolution in the lower 260 m altitude and can be employed as well. Including impacts from waves, currents and sea ice in the NWP models may improve the quality of the winds.

Sea ice, currents and waves are key water variables in the water for OWF siting in the Baltic Sea. For sea ice, satellite data have sufficient spatial and temporal coverage and resolution on sea ice edge and concentration. The period of sea ice thickness data should and can be prolonged by digitising historical high-resolution sea ice charts. Sea ice grounding and ridging information are not available but needed for planning the cable routes. For the in-situ sea current observations, there are significant gaps in EMODnet Physics in the northern and eastern Baltic Sea. Current observations from national projects should be made available, collected and disseminated. For ocean waves, by combining in-situ, satellite and modelled wave data, the purpose of OWF siting can be fitted.

Among the biota variables, birds and marine mammals are the most affected ones. Severe impact on certain bird species cannot be excluded although 99% of the birds can avoid the wind farms. A bird dataset with complete Baltic Sea coverage is needed to alert such potential impacts. HELCOM has relative comprehensive bird and marine mammal databases. EMODnet Biology only has very limited bird dataset covering the central Baltic and Kattegat but no marine mammal data.

Seabed conditions are essential for installing bottom-fixed offshore turbines and cable lines, Current seabed substrate map is useful for general OWF siting purpose but special in-situ geological survey is always needed when doing micro-siting. For bathymetry, EMODnet data has a horizontal resolution of 250 m, which is good for OWF siting feasibility study. However, EMODnet has no seabed slope data which is important for OWF siting. It is recommended that EMODnet Bathymetry should establish a seabed slope dataset derived from the raw bathymetry data. Raw bathymetry data in very shallow waters are also a challenge. Furthermore, only limited amount of sedimentation rate data are available, mainly in the central and southern Baltic Sea. Few sediment transport and grain size data exist in the EMODnet Geology database. It is recommended to build up a sediment transport dataset in EMODnet Geology through both collecting in-situ monitoring data and sediment modelling data.

Human activity data is available from both HELCOM and EMODnet Human activity, which fit for the purpose of the OWF siting feasibility study. Sectorial data (e.g. wind turbine parameters, costs of system, installation, maintenance) are also needed, but are normally not publically accessible. Some of the offshore wind farm data and information can be found in the 4C-Offshore global OWF database. In detailed siting design, more data will need to be requested from national and local authorities in the siting area.

In addition to the above results and recommendations, a few more points should be highlighted for developing or using a marine CDS:

1. Reasons of data inadequacy: in many cases, it is due to lack of data accessibility, appropriate data format and readiness for use rather than lack of observations. This is true for the wind profile, sea ice, bathymetry and OWF sectorial data.
2. Complementary databases: it was found that different data portals such as ICES, HELCOM, EMODnet and SeaDataNet, are complementary. This situation, however, also cause difficulties for users to merging data from different sources. A one-stop data shop such as EMODnet should be established to assemble all the datasets.
3. Integrated use of data: data adequacy also depends on the state-of-the-art of modelling and data assimilation. Products based on in-situ – satellite – model integration are frequently used. With efficient integration methods, major use of the in-situ observations is for validation and assimilation rather than generating final products. This will significantly reduce the number of in-situ stations required.

It should be noted that the variables used in the assessment are not exclusive, only major ones are included. Tourism, for example, is a factor which is affected by OWFs. However, existing research showed that, in many cases, such impacts are positive (Albrecht et al. 2013). Therefore tourism is not a major concern in the assessment.

The current research has limitations. First, it focuses mainly on application for OWF feasibility siting and is limited on the detailed optimal siting. Second, climate change may alter local wind resources significantly (Davy et al. 2018). Wind resource data with reliable statistics and error bar estimates for the future climate (in 20years) should be considered as necessary for the wind farm siting, which is not included in the current research. Third, the methodology used in this paper is very close to the ISO (International Organization for Standardization) standard but not fully yet. In the future ISO standard (for terminology definition) may be applied. Fourth, this paper mainly focuses on the design of the value added products and data adequacy assessment, the realistic OWF siting and optimisation in the Baltic Sea is yet to be done. Last but not the least, the user requirements on data and products for the OWF siting are mainly based on individual expert opinion from the core service providers, downstream service providers and wind farm consultation companies.

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