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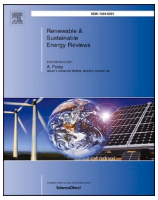

Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design

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ABSTRACT

The global demand for renewable energy is on the rise. Expansion of onshore wind energy is in many parts of the world limited by societal acceptance, and also ecological impacts are a concern. Here, pragmatic methods are developed for the integration of high-dimensional spatial data in offshore wind energy planning. Over 150 spatial data layers are created, which either oppose or support offshore wind energy development, and represent ecological, societal, and economic factors. The method is tested in Finland, where interest in developing offshore wind energy is growing.

Analyses were done using a spatial prioritization approach, originally developed for the prioritization of high-dimensional ecological data, and rarely used in planning offshore wind energy. When all criteria are integrated, it is possible to find a balanced solution where offshore wind farms cause little disturbance to biodiversity and society, while at the same time yielding high profitability for wind energy production. Earlier proposed areas for offshore wind farms were also evaluated. They were generally well suited for wind power, with the exception of a couple of areas with comparatively high environmental impacts.

As an outcome, new areas well suited for large scale wind power deployment were recognized, where construction costs would be moderate and disturbance to biodiversity, marine industries and people limited. A novel tradeoff visualization method was also developed for the conflicts and synergies of offshore energy deployment, which could ease the dialogue between different stakeholders in a spatial planning context.

Overall, this study provides a generic and transparent approach for well-informed analysis of offshore wind energy development potential when conflict resolution between biodiversity, societal factors and economic profits is needed. The proposed approach is replicable elsewhere in the world. It is also structurally suitable for the planning of impact avoidance and conflict resolution in the context of other forms of construction or resource extraction.

1. Introduction

The global demand for renewable energy is expanding in the attempt to mitigate the impacts of climate change. Offshore wind energy is, alongside with other “green” forms of energy, at the core of seeking carbon-neutrality of various countries. Based on the International Energy Agency, offshore wind energy could become the main source of power generation in Europe by 2042 [1]. Consequently, interest in offshore wind power is on the rise. By 2020, already 25 GW had been installed in Europe, and according to the latest projections by Wind Europe, 450 GW could be deployed by 2050 [2].

Onshore wind energy competes with other land use types. It can cause harm to terrestrial ecosystems, impact wildlife populations, and

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List of abbreviations:

GIS	Geographic Information Systems
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
OWF	Offshore Wind Farms

cause disturbance to people [3]. These can be seen as a severe hindrance to increasing land-based wind energy production. While at sea there may be fewer competing interests and conflicts than on land, deployment of offshore wind energy still needs to account for societal and ecological factors, in addition to the economic feasibility of energy production.

Deployment of offshore wind farms (OWF) conflicts with various human interests, as the social acceptance of OWF projects involves socio-cultural, political, economic and community dimensions [4,5]. While public opinion may be broadly supportive towards renewable energy policies [6,7], OWF may face societal opposition and disapproval, especially from close-by communities [8]. Windfarm installations may cause various disturbances, such as undesired landscape effects, visual interference (including flickering) and noise [9–13]. Attitudes and opinions towards OWF however vary, and depend on underlying values, likely impacts of the proposed OWF project, and beliefs about the ocean [14,15]. For instance, OWF may also be viewed as visually appealing, which may represent a shift in attitudes towards clean energy future [11]. OWF also compete over marine space with other sectors, including aquaculture, tourism, shipping, extraction of seabed resources and commercial fishing. Countries dependent on tourism may experience economic losses, as offshore windfarms may deter natural landscapes and thus recreational visits [16]. Co-location of activities within OWF may be one of the solutions, as pressure on existing sea space continues [17]. Conflicts are expected to rise as utilization of the coastal and offshore areas intensifies and expands with increasing commercial interests in marine materials and resources [18,19].

OWF have direct and indirect negative impacts on marine life in the construction, operational and decommissioning phase. Most of the severe, negative impacts occur during construction of OWF, while lower impacts can be expected in the operational phase. OWF pose threat to birds, fish, marine mammals, and bats, for instance in the form of collision mortality, displacement from breeding or nesting areas, disruption of migration corridors, barrier/avoidance effects on movement, acoustic and electromagnetic disturbances, changes in food supply, and habitat degradation [20–26]. Detrimental effects also impact highly sensitive benthic organisms, and include habitat disturbance and loss, changes in community composition, colonization of non-indigenous species, and changes in ecological functions [27–30]. Moreover, cascading effects of OWF on benthic ecosystem, and the potential for benthic recovery remain unclear [28,31].

Benefits of OWF for marine life have also been demonstrated (in the operational phase), by providing protection, new habitats, resting areas and food resources [23,32–36]. Some studies have also shown that species abundances are higher, and species assemblages more diverse within OWF [33,37–40]. Extensive evidence is lacking of the impacts of decommissioning phase on marine life [41]. The removal of OWF differs only slightly from the construction phase (e.g., no intense modification of the seabed), thus the environmental impacts can also be expected to be similar. Partial removal of installations has suggested to be an option with smaller environmental impacts, and an alternative to maintain potential environmental benefits [42]. Negative impacts of OWF on biodiversity, marine industries, livelihoods, and people, can be alleviated with careful planning, which also considers the profitability of offshore wind energy.

Previous studies about locating suitable areas for offshore wind energy have relied mainly on GIS-based methods, and such research is growing over time [43]. Various studies have analyzed the economic feasibility of offshore wind energy production [44–49], needed wind resources [50,51], environmental impacts [52,53], visibility [54–56], stakeholder involvement [57,58], and the overall suitability of areas for wind energy production on multiple geographical scales, with study-specific exclusion and zoning rules [46,59–65]. Some studies have also coupled multi-criteria decision frameworks with GIS [59,66,67].

One problem of common GIS-based methods is that analyses may lose the dimensionality of data in the process and require heavy a-priori classification of individual GIS layers into areas suitable and not, which is not very realistic for factors that in reality measure on a continuous scale and for example decline by distance. This may also result in undesired societal and environmental impacts in the OWF deployment phase and leave more room for non-scientific speculation about thresholds of harm and interactions between factors that should be taken into account in the siting of OWF.

As a major difference to the present work, previous studies have mainly concentrated on evaluating best areas for OWF deployment based only on individual type of factor/constraint, such as wind resources, marine birds, benthic habitats or cost of offshore energy installations [51,68–71]. Because OWF nevertheless have simultaneous impacts in multiple dimensions, integrative studies, such as the present work, are needed.

In response to the design problem and research gap, the main components of OWF development are here integrated: economics, societal consequences of OWF deployment, disturbance to people, maritime sectors, and biodiversity. Generic methods of spatial (conservation) prioritization are adapted to develop an approach that is pragmatic, transparent, operationally feasible and replicable elsewhere. One of the goals of this study is to also provide an approach for OWF suitability analysis using spatial prioritization, as it is rarely used method in OWF siting. The outputs of this study, such as OWF suitability maps, can support the efforts of environmental administration, regional councils, and the energy industry in ecologically and societally well-informed planning of wind power. A novel tradeoff visualization method was also developed for the conflicts and synergies of OWF deployment, which could ease the dialogue between different stakeholders in a spatial planning context.

Research on OWF site suitability have usually addressed less than ten spatial parameters, of which most common ones are: water depth, distance to ports, and conservation areas [43]. With respect to underlying data, 154 spatial data layers were developed here (Fig. 1), at a 100 m analysis resolution, representing biodiversity, societal factors (human activities and maritime industries), and the cost structure of OWF. The data broadly divide into factors that support or oppose wind farm development. Comprehensive information of the underwater nature is not usually available. The biodiversity component here relies on extensive knowledge of underwater species and habitats, based on a systematic survey of 140 000 underwater sites, which provides basis for high-resolution species distribution modelling [72]. Additional data was sourced for birds, marine mammals and fish. The species and habitats included in the present analysis were chosen so that they might be impacted by the typical negative effects of offshore wind farms, including habitat loss, bird collisions, and underwater noise. The societal component of the analysis includes information about legislative restrictions and expected disturbance to people or their livelihoods, which need to be thoroughly evaluated, if legitimacy and acceptance of OWF projects is expected.

The economic cost component is based on a novel spatial Life Cycle Cost (LCC) model, which determines the levelized cost of energy (LCOE) at a given geographical location, while accounting for technological properties of OWF (e.g. nameplate power rating, height), environmental properties (e.g. wind speed, seafloor type), and distance-based factors that affect the installation and commissioning, operation and

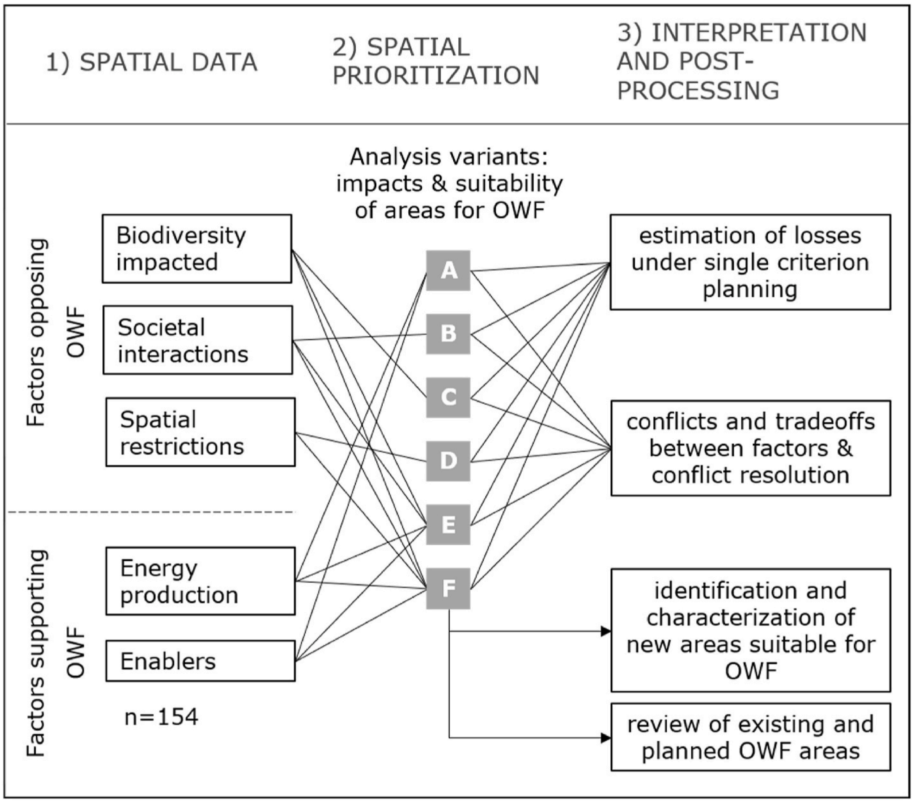

Fig. 1. Schematic of the workflow of the present study.

maintenance, and decommissioning costs [73]. An overview of the workflow is presented in Fig. 1.

Overall, the present work provides a generic model for spatial prioritization when potential economic benefit is to be balanced with many ecological and societal factors. While relevance and availability of individual data layers would depend on region and case, the approach presented is not limited to wind power. It can support the solution of different types of design problems, such as planning and optimization for other types of renewables and resource use.

2. Methods

2.1. Spatial prioritization

Spatial prioritization has rarely been used in analyzing OWF suitability. It has usually been used in biological conservation planning, in the development of protected area networks [72,74,75]. Another application is ecological impact avoidance in the context of economic development or resource extraction [76]. Spatial planning for impact avoidance attempts to implement conflict resolution between biodiversity and human land uses. Also ecological responses, such as connectivity, can be approximated in prioritization models [77], including in the marine realm [78].

Zonation is an approach and software for spatial prioritization. It operates on spatial layers that can represent the distribution of biodiversity features, threats, costs, and societal/administrative restrictions [79]. Prioritization using Zonation is effectively a balancing operation, in which partially aligned or opposing factors are used to produce a ranking through the landscape [80]. The following analytical characteristics of Zonation are relevant for the present application: (i) ability to do national-scale high-resolution analysis that can be linked to on-the-ground decisions; (ii) maintenance of the balance between all features throughout the ranking, meaning e.g. that no species or habitat can be completely lost to a wind farm; human disturbance will likewise be avoided; (iii) avoidance of harm to narrow range biodiversity or societal features, (iv) ability to account for costs or opportunity costs, which is here utilized for OWF economics, and (v) ability to both identify new areas and evaluate proposed areas for OWF.

General options for data treatment and parameters for spatial prioritization are shown in Table 1. The quantitative characteristics of the priority rank map generated by Zonation can be evaluated via another standard output, the so-called performance curves.

The setup was constructed so that one end of the priority ranking holds areas economically good for wind power but where ecological or societal concerns were low. The other end of the ranking is the opposite, where producing wind energy is expensive, and ecological and/or societal impacts are high. Table 1 summarizes data baskets (types) used in the analysis (upper left column), technical options for their treatment (upper right column), and explanation for what treatment(s) would be appropriate for each data basket (lower part of the table). While the present context is offshore wind power, the same structural components and options would apply to other impact avoidance applications elsewhere in the world.

2.2. Study area

The planning area covers the Finnish territorial waters and exclusive economic zone in the northern Baltic Sea, an area of 81 500 km^2 of shallow waters (mean depth of only 48 m) with tens of thousands of islands and skerries. The Finnish marine areas host relatively few species of marine and freshwater origin [81,82]. Marine areas suffer from eutrophication, increasing anthropogenic disturbance, and hypoxia [83–85]. Given the pre-existing pressures, any large-scale projects including major wind farms should be evaluated also from the ecological and societal perspectives.

Only one offshore wind farm (Tahkoluoto, 40 MW) exists on the Bothnian coast of Finland. The interest for developing OWF is on the rise, and the planned OWF capacity is 2800 MW (based on information

Table 1
Treatment of different types of data in spatial prioritization using Zonation.

Data basket	General data treatment options in Zonation
(1) Biodiversity; potential disturbance to species or habitats	(1) Selection of input data and external pre-processing of input layers. Option always available for any analysis.
(2) Economics; here cost of energy, could also be profitability, if known	(2) Cut with analysis area mask. General option for cutting analysis area to the context of relevance.
(3) Societal interactions	(3) Use of hierarchic analysis to account for pre-specified land use class.
(3a) Restrictions; no-go zones such as military areas or neighbourhoods of airports	(4) Connectivity interactions; positive or negative. (see e.g. Lehtomäki and Moilanen [77] for summary)
(3b) Deterrent; economic opportunity cost to a stakeholder	(5) Analysis: positive (5a) vs negative (5b) weighting of features. With 5a (5b), high local value for factor leads to increase (decrease) in priority.
(3c) Extra administrative difficulty, uncertainty or expense to the constructor of the wind farm	(6) Automated post-processing inside Zonation.
(3d) Disturbance to people	(7) External post-processing, including such as GIS overlay.
(4) Enablers	(8) Contrasts between analysis variants.
(5) Existing or planned wind farm locations	

Connection of data basket to appropriate treatment

Basket	Treatment	Explanation
1	5a, 5b, 4	5a for desirable species/habitats; 5b for (undesirable) invasive species or pressures. Normal use of connectivity features applies (see Lehtomäki and Moilanen [77]).
2	5	5a if construction cost used, 5b if profitability used. Low construction cost is good for wind power as is high profitability.
3a	3	Use of hierarchic analysis to mask no go areas into high priorities.
3b	5a	Opportunity costs for stakeholders (livelihoods) oppose wind power and hence increase priority ranks in the area.
3c	5a	Lowers suitability for wind power and hence increases priority rank.
3d	5a	If presence of wind turbine in area causes disturbance to people, the (ecological/societal) priority of the area should go up.
4	5b	The presence of wind farm enablers should lower priorities.
5	3 + 6	Combination of hierarchic analysis and automated post-processing output for planned wind power areas.

from 1/2021, the Finnish Wind Power Association). The first Maritime spatial plan 2030 for Finland provides a strategic background for guiding the use of areas (https://www.merialuesuunnittelu.fi/en/msp-draft-2030/). More detailed regional plans set out land use principles (e.g. for OWF), and designate areas for regional development (in accordance with Land Use and Building Act 132/1999). The areas which are recognized as potentially suitable for OWF development are in the hands of developers and planners, but to our knowledge, there does not exist any prior (extensive) prioritization analysis for OWF.

2.3. Data for wind farm site optimization

This section summarizes the ecological, societal and economic data used for prioritization (section 2.1). Details of the data and analyses can be found from the Supplementary Table 1 and Supplement 2. Much of the underwater biodiversity data was developed by Virtanen et al. [72].

2.3.1. Biodiversity

Impacts of OWF on marine nature are usually described as negative, although there may also exist positive synergies: OWF may act as artificial habitats, or as no-take zones – areas where marine life is “protected” [86,87]. The present study concentrates on ecological impact avoidance, and thus OWF are seen as negative to marine life.

Estimation of OWF impacts on marine species and habitats have been usually hindered by the lack of extensive scholarly work on underwater biodiversity. A national mapping project, the Finnish Inventory Programme for the Underwater Marine Environment (VELMU), has collected extensive information on species and habitats since 2004. Over the years, information has accumulated from over 160 000 sites (at the time of writing 10/2021) on threatened species, communities and habitats. The database forms a basis for modelling the ranges of various species, including vascular plants, algae, charophytes, water mosses and invertebrates. The species and habitats included in the present analysis were chosen so that they might be impacted by the typical negative effects of offshore wind farms, including habitat loss and disturbance (details in Supplementary Table 1).

Marine underwater habitats described by the EU Habitats Directive (Council Directive 92/43/EEC) have been mapped and reported by the environmental administration [88]. Eight habitats associated with marine environments were included in analyses, such as sandbanks, coastal lagoons and reefs [as described by Ref. [89]]. Data was derived from official, national data sources, used in the Habitats Directive reporting in 2019.

The analyses also included information on the Baltic Sea habitat types, which are formed by a dominating species or species group. Their threat status was assessed for the second time in 2018, based on the international IUCN Red List of Ecosystems methodology [90]. Most of the habitat types considered here have been classified as threatened, such as benthic habitats characterized by eelgrass (*Zostera marina*). In addition to underwater habitats and habitat types, geological diversity was described by geodiversity and patchiness of geological features [91]. As a precaution, the distribution of iron-manganese concretions was also considered, as they may provide habitats for various species [92,93].

Essential coastal fish reproduction habitats for European perch (*Perca fluviatilis*), pikeperch (*Sander lucioperca*) and smelt (*Osmerus eperlanus*) were also incorporated. Perch and pikeperch are important top predators in the coastal system, and for them as well as for smelt, spatially limited and thus valuable coastal reproduction habitats are typical [94]. All three fish species are valued target species by both commercial and recreational fishermen [95].

Of the above-water biodiversity, main migration routes of migratory birds [96] were considered. Also the nesting sites and habitat-use of subadult white-tailed eagle, currently under protection, were also taken into account [97]. Known grey seal moulting islets were considered important stationary territories of highly mobile seal species [98] and were included in the prioritization.

Various types of protected areas were also accounted for (depending on the level of restrictions): Natura 2000 areas, HELCOM MPAs, national parks, nature reserves, private protected areas, seal protection areas, Ramsar sites, fisheries restriction zones, and internationally, nationally and regionally important bird areas (IBA, FINIBA, MAALI, respectively).

2.3.2. Societal interactions

Main disturbances of OWF to people are visual intrusion and noise, concerns of the damage caused to marine life and environment, and competition with other sectors over marine space [9–11,99]. Betakova et al. [13] showed that negative visual impacts of OWF disappeared after

10 km, whereas Sullivan et al. [9] concluded that OWF are a major visual focus up to 16 km. The visual sensitivity towards OWF however depends on attitudes, overall aesthetic value of the seascape, and characteristics of the OWF, such as number of turbines [11,13]. As a precautionary approach, and following Sullivan et al. [9], landscape deterioration up to 16 km for both housing and cottages was acknowledged by a viewshed analysis, in order to find locations where the visibility of OWF might cause less resistance. The analysis also included the height of vegetation and local topography from laser scanning surveys [100] (details in Supplementary Table 1). Similarly, the level of noise as a declining function of distance was analyzed to both permanent housing and summer cottages.

The potential accident risk for people by OWF collapse or detachable parts was accounted for with a safety zone of 300 m from the coastline [101]. Data was also developed that describe pristine coastal areas (potential landscape and ecosystem service value) [10], and infrastructural uses of the marine environment, such as docks. Offshore installations may also physically damage sites that are important for cultural heritage. Thus, UNESCO World Heritage sites, nationally valuable built cultural environments, nationally valuable landscapes and geological formations, and known underwater ancient monuments, were included (details in Supplementary Table 1). One of the societal concerns of OWF is impacts on boating. For instance, Dalton et al. [102] showed that recreational boating experience is deteriorated close to OWF. Thus, information was added on the boating intensity, boating services and their accessibility, as a proxy for spatial preferences of recreational boaters [103].

With respect to other maritime sectors, both commercial fishing and aquaculture compete over marine space with OWF [104,105]. Coastal commercial fishing was incorporated into the study by including coastal trap net and gillnet fishing areas mapped by fishermen [106]. Trawling of pelagic fish was introduced in the analyses as fishing effort by gear type, which relies on information gathered and combined from Automatic Identification System (AIS), satellites and terrestrial receivers [107]. Present marine aquaculture sites and potential aquaculture locations in government-owned water areas were also included in the analyses [108].

In addition, restriction areas were included on a three-level hierarchy, depending on the level of restrictions (see Supplementary Table 1). Strict restrictions represent for instance obstacle limitation surfaces limiting turbine or building heights in airspace, and weather radars.

2.4. *Energy production – spatial life cycle cost analysis*

Compared to onshore wind farms, marine conditions pose challenges to OWF development. OWF projects require different technology, electrical infrastructure, and logistics for installation and maintenance. Construction of OWF is inherently expensive, as installation depends on special equipment, distance to the electricity grid – which can be tens of kilometers, and on the scale of wind farm, i.e. installed capacity to produce energy. The cost of producing offshore energy has however decreased, due to technological advances and optimization of OWF processes and components.

Life Cycle Cost analysis (LCC) focuses on identifying all significant cost components over a project's lifetime. Here the economic potential of offshore wind energy was estimated using spatial Life Cycle Cost (sLCC) analysis (See Supplement 2), following a framework developed by Lappalainen [73]. In broad terms, costs were divided to five different life cycle phases: Development and consenting (D&C), Production and Acquisition (P&A), Installation and Commissioning (I&C), Operation and Maintenance (O&M) and Decommissioning and Disposal (D&D) [109,110]. The time value of money was accounted for in the contributions of cost components to the sLCC. The modelled sLCC layer was entered into spatial prioritization as a relatively highly weighted component.

Spatial LCC analysis was based on water depth, distances to closest I&C and O&M ports, closest onshore substation, length of sub-sea export cable, seabed substrate and Weibull distribution parameters α and k. The time component was included via use of the levelized cost of energy (LCOE). LCOE is a common measure for average financial cost of produced energy over a project lifetime, describing the net present value of an energy unit (e.g. in €/MWh).

LCOE was calculated spatially based on cost structure and energy production potential that were both influenced by wind farm location through various spatial variables (Supplement 2, examples below). Compared to the original framework [73], here the LCOE was expanded to cover the whole coast of Finland, and wind parameters were based on the ERA-5 reanalysis.

Distance to I&C port was calculated from 13 largest potential I&C ports using deep fairways and sea areas deeper than 10 m as a cost surface, while accounting for the barriers in the land (sea)scape. The distance to O&M port was obtained similarly to I&C ports, using a potential port network of 31 ports and 5 m deep areas and fairways as the cost surface.

The locations of onshore power substations were based on the following analysis. Potential 400 kV transmission grid connection points (switchyards) along the coast have been mapped by the Finnish transmission system operator, Fingrid Oyj. An aerial 400 kV powerline was assumed to be built from the switchyards to the onshore substations located on the shoreline. The potential locations of onshore substations were chosen from aerial images based on: local minimum on the cost of the aerial 400 kV powerline and suitable area for the substation near the shore. The cost for the powerline was obtained from cost distance analysis from switchyards to shoreline using CORINE land cover 2018 and protection areas as barriers in the cost surface raster. The identity of the closest onshore substation and the length of the subsea export cable were calculated from the onshore substation sites. Later on, the identity of the nearest onshore substation was linked to the cost of the aerial powerline to the 400 kV transmission network including the connection cost.

The estimate for annual energy production was obtained from Weibull distribution data for wind speed. Distribution parameters at 100 m height [111] were used and amended to cover the open sea with ERA-5 reanalysis for the period 1979–2018 by the Finnish Meteorological Institute, with ERA-5 data provided with a resolution of ~31 km [112,113]. Moreover, the data were downloaded with a 0.2-degree resolution and this dataset was used for calculating Weibull parameters.

Annual sea ice increases the construction and maintenance costs of OWF, and thus also has an effect on the LCOE. Ice cover is one of the reasons why wind farms in the marine areas are not yet common. Spatial LCC analysis was originally developed for marine areas that do not freeze. Here, variation in ice conditions was included using a data layer containing 50-year maximum level ice thickness. This data is based on the Finnish Ice Service's ice charts from the winters 1980/1981 to 2018/2019. The 50-year maximum level ice thickness was calculated from the annual maxima as described by Makkonen and Tikanmäki [114]. More details of the data can be found from Tikanmäki et al. [115].

2.4.1. *Enablers*

Development of OWF has been shown to be less acceptable in pristine and natural areas [10,11,116]. Thus, industrial areas, such as large ports or factories, can be considered to have lower landscape value, as the landscape near the industrial site has already been altered. Hence, as an indication of opportunity, a spatial layer representing the neighbourhoods of large industrial areas was added. In addition, sea areas suffering from long-term hypoxia ($O_2 < 2$ mg L^{-1}) and those having *Beggiatoa* sp. bacterial mats that indicate hypoxia, are typically dead zones, or at least species-poor. These areas may thus be considered favourable for large scale construction from the perspective of ecological impact avoidance. Hence, distribution of hypoxic seafloors and *Beggiatoa* sp. were included in the study as an enabling factor [based on data from 72, 85].

3. Results

Spatial prioritization was carried out for locating areas most suitable for offshore wind farms in the Finnish marine waters, while balancing between competing interests: biodiversity, societal and economic values. The analysis also shows areas that are less suitable for OWF development. In each map of Fig. 2 the color scale shows the priority ranking, ranging from dark blue for areas most suitable for offshore windfarms to light green for areas with high conflict with biodiversity and societal considerations. The first four panels show how OWF could be placed when prioritization is based on (A) economics alone, (B) societal factors alone, (C) ecological factors alone, and (D) restrictions. The final two panels show the priority ranking arising from integrated analysis, with (F) and without (E) societal restrictions. Loss curves shown in insets summarize the cumulative occurrences of features in each data basket (economy, society, biodiversity) inside the respective top priority areas for wind farms. Note that in single-criterion analyses (A), (B) and (C) also other factors are included for evaluation, but with zero weight, so they do not influence the prioritization.

As this research concentrates on ecological and societal impact avoidance, economically viable areas are sought that are not occupied by high biodiversity and which are also acceptable from societal perspectives. Such areas have ranks that vary from 75% to 100% in Fig. 2. The suitability maps of Fig. (2) pair up with the group-specific mean performance curves shown in insets. A mean performance curve at rank x% shows the mean coverage of the occurrences of the features of the group in the areas corresponding to ranks 0% to x% in the seascape. Conversely, the mean coverage of the group in areas corresponding to ranks x% to 100% is one minus the value of the performance curve at x %. For instance, the curve for biodiversity in analysis (Fig. 2C) shows that the top 25% areas for wind farms only cover a few percent of biodiversity feature distributions.

Fig. 2A shows the most optimal areas for offshore windfarms based solely on economical profitability of producing wind power. Shown in dark blue (>75%), the whole southern part of the Finnish marine area seems promising for offshore windfarms. Overall, the economic feasibility of areas – based on the life cycle costs of OWF, mainly depends on the size and capacity of planned OWF (number of turbines, turbine capacity factor, turbine power rating), and wind conditions. Other factors only have a moderate effect. Large farm sizes and locations near the coastline provide the most cost-efficient solutions, as cost of energy increases linearly with increasing distance (details in Supplement 2). Shown in green (<25%), deployment of wind farms further out at open sea becomes more expensive and thus less feasible, because of higher construction and maintenance costs, which correlate with increasing depth, longer export cables and distance to ports, and in the northern Bothnian Bay, thick sea ice. Suitability of areas for wind farms shifts drastically in analysis variants of Fig. 2B and C, which consider only the society and biodiversity, respectively. In both cases, the best areas for offshore windfarms are located further away from the coastline, as various human activities take place near the coastline and because shallow, photic areas are rich in biodiversity. This can be also seen in the

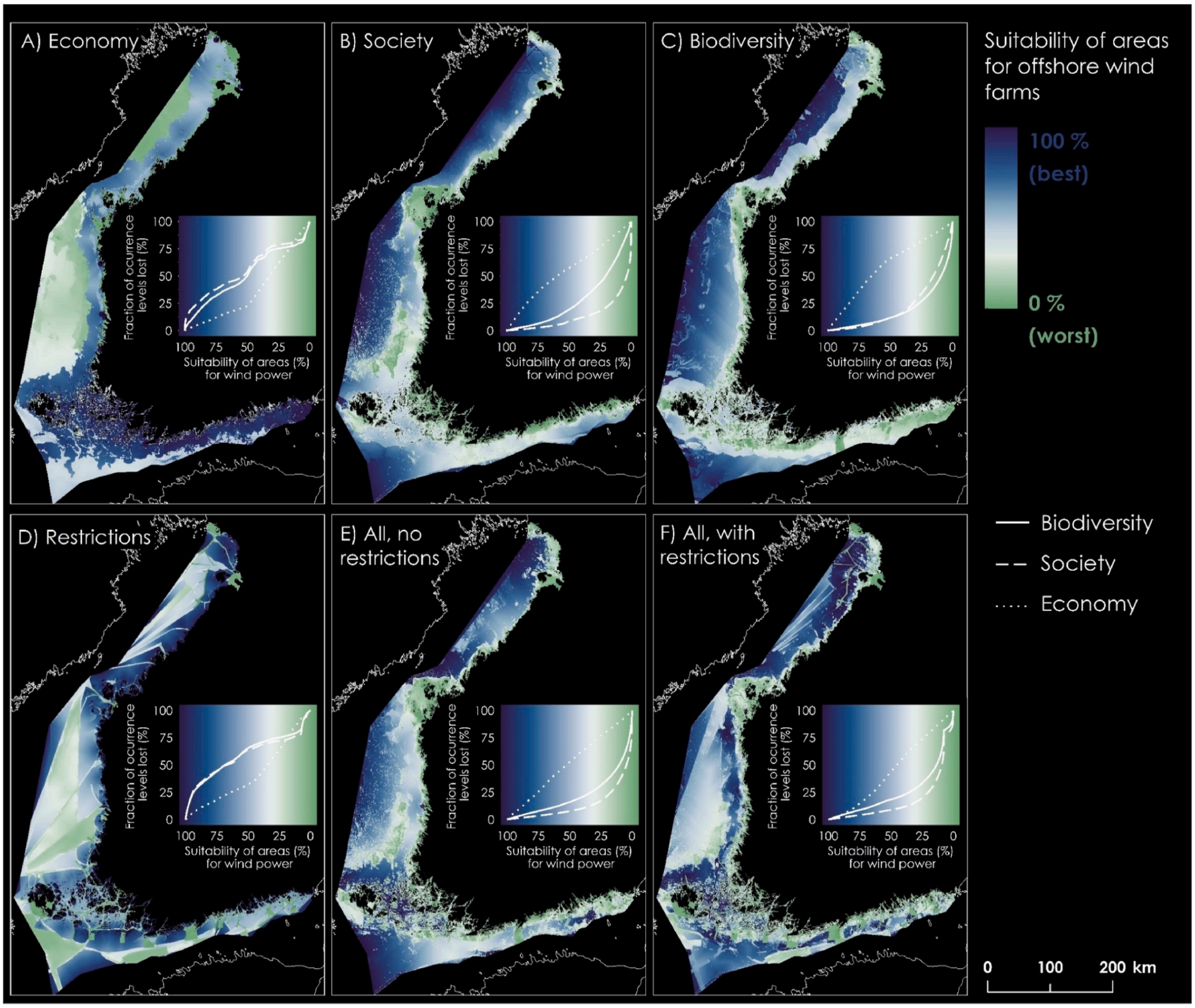

Fig. 2. Different analysis versions of the suitability of areas for offshore windfarms.

rather similar trends for the performance curves analyses (2B) and (2C), where the curves for biodiversity and the society follow each other closely in a concave form, suggesting that the ecologically most valuable areas and anthropogenic activities are both concentrated and overlapping.

In solutions (2B) and (2C) the close to diagonal shape of the economy curve (dashed line) suggests a rapid loss of areas where construction costs would be low to moderate. This means that, if decisions for the offshore wind farm sites were to be based only on ecological and societal considerations, energy production would need to move to more costly areas at the open sea. Analysis solution (2D) shows the most optimal places if only present administrative restrictions, i.e. no-go areas such as fairways or military areas, are considered.

It can be seen in more detail from Fig. 3 that if planning were to be based on one criterion alone, there would be major losses to the other criteria not accounted for. For example, if analysis is based on economy alone (Fig. 2A; Fig. 3A), the 25% top priority areas would lose on a significant 30% of the original occurrence levels of biodiversity. This solution would likewise cause the most harm to people and the society (almost 50% of the society occurrence levels lost), with doubtful societal acceptance if wind farms were to be planned, e.g., close to summer houses. If wind farm placement was based on biodiversity alone (Fig. 3C), the cost level would increase to multiple of that in the economics-only analysis, and the deployment of OWF would most likely become economically infeasible. The analysis solution which relies only on legal constraints and restrictions (Fig. 3D), has the highest losses for biodiversity and society (>50% lost).

Bringing competing factors together, (2E) and (2F) show the main analyses; the integrated balanced solutions, by which conflict resolution can be achieved. In these analyses, economics, society and biodiversity are all accounted for, both with and without restrictions. When all criteria are considered together, it is possible to find a placement for wind parks that causes very little disturbance to biodiversity or the society, while at the same time yielding almost as high profitability for wind energy production as with the economy-alone solution. Hence, conflict resolution between biodiversity, societal factors and economic profits can in this case be achieved.

Potential conflicts between economic considerations, biodiversity and the society are further explored in Fig. 4, which maps single-criterion analyses (2A, 2B and 2C) onto an RGB color composite map, thereby highlighting the geographical overlap/separation of biodiversity (green), societal factors (red) and profitability of wind energy production (blue). As a technical detail, to show highest conflicts in bright colors, the priority rank from each analysis (2A, 2B and 2C) has been multiplied with one minus the value of the mean performance curve for the same rank in the same analysis, and the resulting number has then been mapped onto a 0–255 color brightness scale. Doing so also accounts for aggregation of features in the visualization.

For instance, in the color composite pink represents potential conflict between economy and the society, and cyan between economy and biodiversity. The large bluish areas in Fig. (4) indicate the broad geographic extent of areas economically feasible for offshore wind farms, which is in contrast to biodiversity and societal factors, which are more aggregated near the coastline. Wind power (economy) and societal factors conflict in many coastal areas (indicated by purple color in Fig. 4), which suggests that siting of offshore energy in these areas would most probably face social disapproval and resistance. The fronts of large coastal cities are typically low in biodiversity, due to anthropogenic disturbance and degraded water quality, which would make them potentially suitable for wind power, but societal concerns are highest in these areas. The outer archipelago, in turn, is less used and occupied by people, but it holds high ecological values. Furthermore, there are geographical differences: societal pressures are comparatively low in the north (Fig. 2B, >75%), because of lower population densities, but ecological values are high (Fig. 2C, <25%) and winter ice conditions make construction of wind power expensive (Fig. 2A, <25%). In the south, especially in the Gulf of Finland and in parts of the Archipelago Sea, there are many administrative restrictions, which can slow down or prevent infrastructure development.

Potential sites for the deployment of offshore wind energy are illustrated based on the analysis variant shown in Fig. 2F, by selecting suitable candidate areas from the top 25% fraction of the seascape for wind power. For demonstration, three sizes for potential offshore wind farms were chosen, 25, 100 and > 200 km^2 and as an additional criterion, the space between the sites had to be over 10 km in order to maintain optimal wind conditions. The small and medium-sized OWF sites were randomly placed in the seascape, while the larger ones were chosen, to keep the design of the potential OWF intact and in the top 25% fraction.

Fig. 5 shows 15 illustrative potential sites that somewhat satisfy these preconditions. The most potential large-scale (>200 km^2) sites are located in the Bothnian Sea, medium-scale (100 km^2) sites in the Bothnian Bay, and some smaller (25 km^2) sites in the Gulf of Finland. The qualities of these sites are further characterized in Table 2, which summarizes the average priority ranks and feature densities of the suggested sites. The interpretation of feature density is the density at which features of that group occur in the area compared to the whole seascape on average. Feature density is 1,0 for a completely average

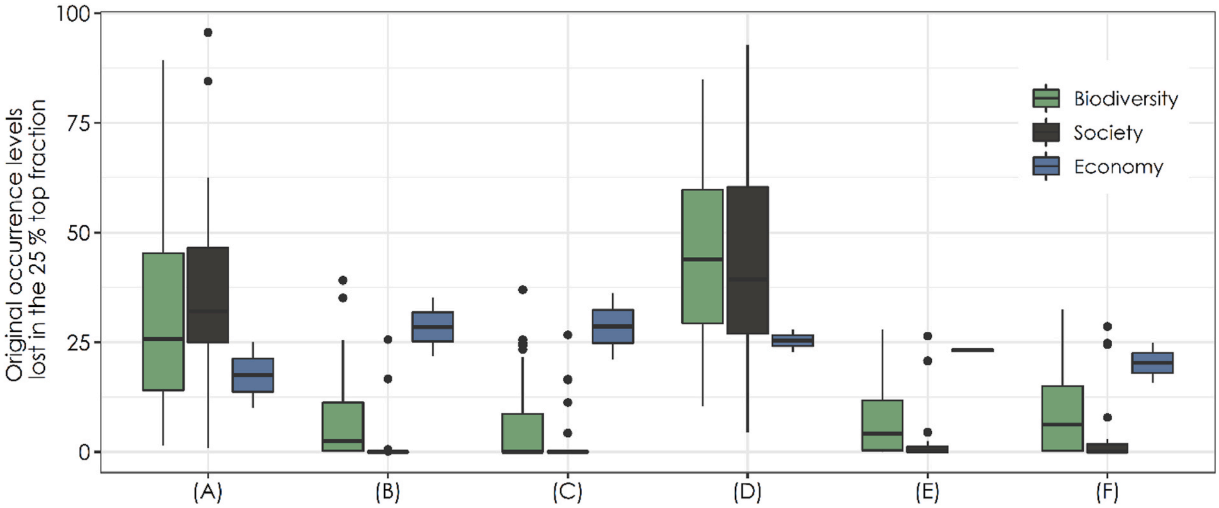

Fig. 3. Box plot of feature occurrence levels per feature group: biodiversity, society, and economy – calculated for the 25% top fraction area for wind power for each of the analysis variants (A-F, cf. Fig. 2).

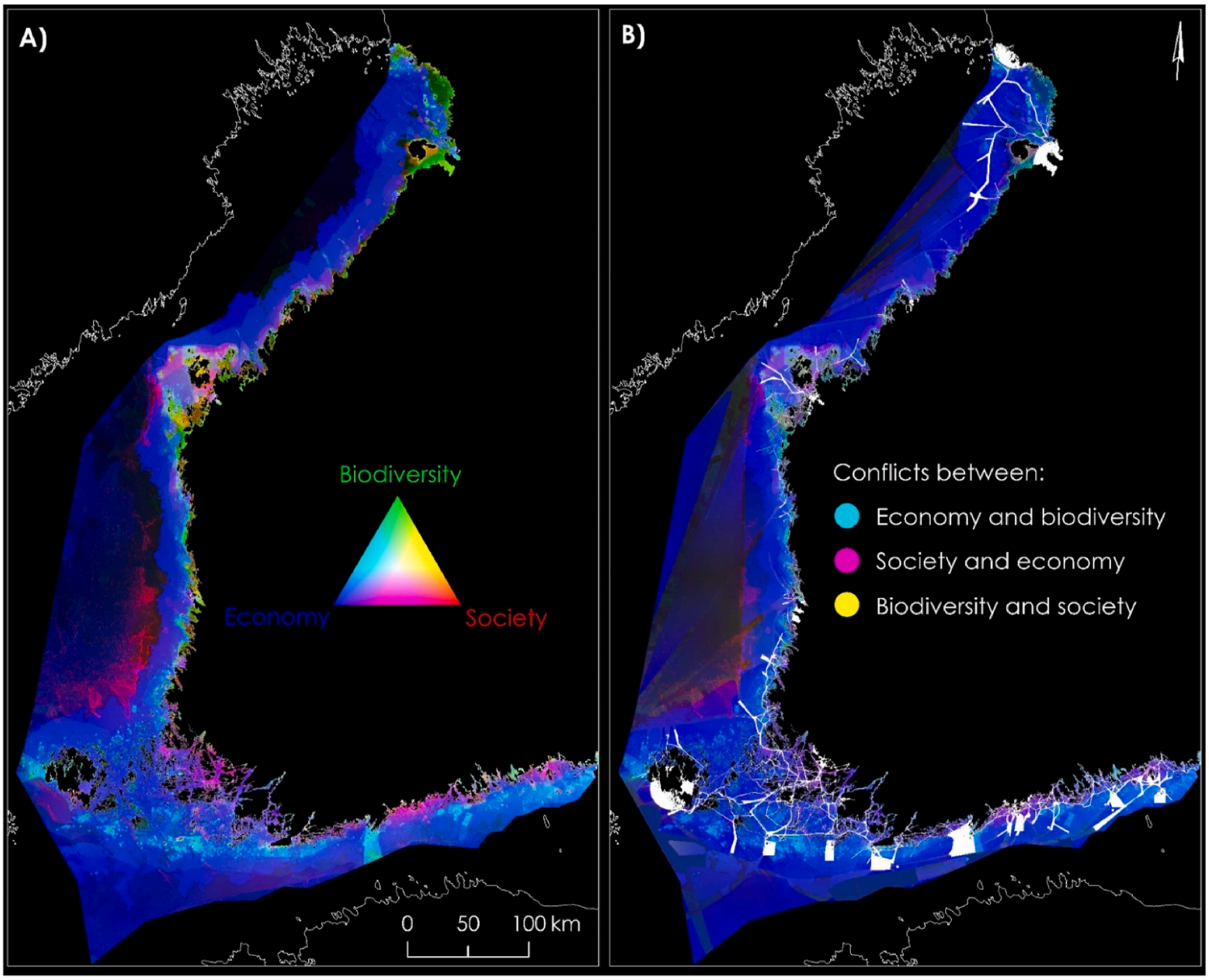

Fig. 4. Visualization of conflicts between biodiversity, windfarm economy and the society, (A) shown by mapping single-criterion analyses (2A-C) onto RGB color components, (B) with administrative restrictions overlaid in white. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

area; here numbers less than one, which indicate lack of occurrences, are preferable. Overall, the proposed areas lack known administrative restrictions, are low in biodiversity content (e.g. site 5, feature density 0,08), are low in societal importance (e.g. site 2, feature density 0,07), and have low to moderate construction costs, i.e., have high profitability of wind energy production (e.g. site 12, feature density 0,07). The existing and the known, proposed OWF were also evaluated, and it was discovered that some of the already planned sites hold high ecological value, may experience societal resistance, and have lower wind energy profitability (e.g. site e and i, Table 2).

4. Discussion

The methods described here allow high-resolution, data-rich, spatial prioritization impact avoidance applications over large areas. These applications effectively implement spatial conflict resolution between economic considerations and potential damage or disturbance to the environment, people, and their livelihoods. Societal considerations divide between strict limitations to development and cumulative negative influences that should best be avoided. In the process, it would be possible to also balance benefits and costs across multiple stakeholders, conditional on the availability of some stakeholder-specific input layers. While the present work is about planning for OWF in the context of ecosystem-based marine spatial planning, the same approach applies to other marine applications such as planning for aquaculture locations or seabed mining. Applications could also be terrestrial instead of marine. Individual data layers of relevance would depend on region and specifics of the case, but the overall analysis setup and analysis flow would be relatively independent from case-specific detail.

OWF, biodiversity and societal factors are not independent. Societal and economic activity are inherently linked. OWF and societal factors have a negative interaction, as OWF may cause disturbance to people (sound, visual effects) and their livelihoods (exclusion of boating/fishing inside the wind parks). On the other hand, OWF may also provide new opportunities (jobs, tax revenue). OWF should not ideally be situated where there are large opportunity costs to people and their livelihoods. Biodiversity on the other hand may enable resource extraction, livelihoods for people and recreation, but at the same time societal/economic pressure will inevitably harm biodiversity. Overall, some spatial separation of biodiversity conservation, societal activity and OWF is desirable. It is also broadly useful for land-use and sea-use planning to understand the relative importance of areas to biodiversity, societal activities and OWF, as shown by Fig. 2.

This analysis identified areas potentially highly suitable for offshore wind farm development in the Finnish sea area. The most suitable large areas are at the Bothnian Sea and the Bothnian Bay (Fig. 2F, suitability >75%). Some smaller areas were also randomly recognized as suitable in the Gulf of Finland (Fig. 5, sites 2 and 3), although these are in reality unlikely due to strategical, national defense reasons, as they are situated close to the capital city. Overall, the most potential areas for OWF are located further away from the coastline, where various human activities take place and where the ecologically most valuable areas are located.

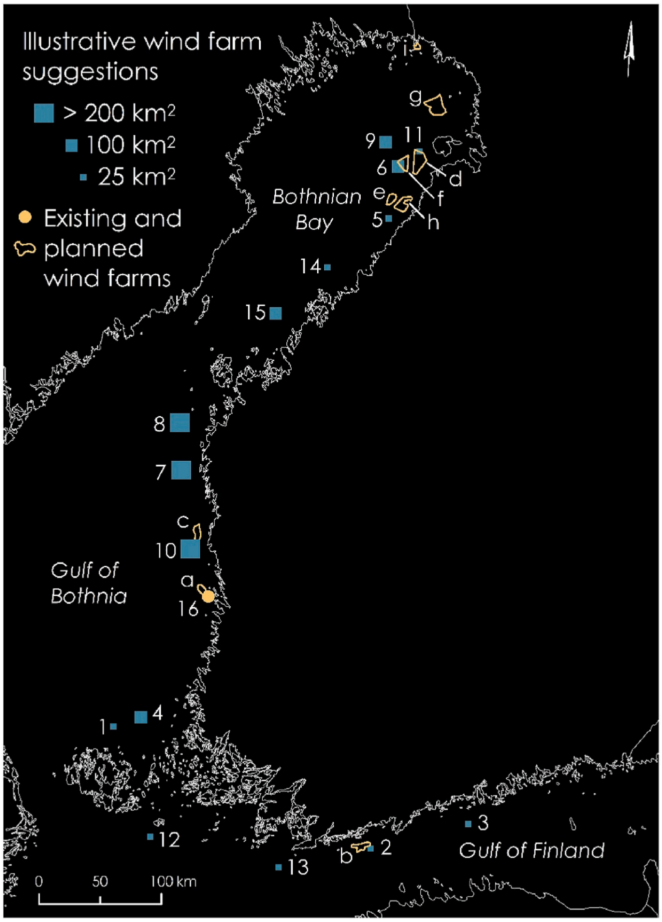

Fig. 5. Existing and planned wind farms in orange and illustrative example locations for new 25, 100 and > 200 km^2 wind farms in blue. The area numbers and letters link to area-specific information in Table 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Such results are expected from the shallow marine environments where the photic zone is limited, and which typically host a variety of sensitive habitats and species [72]. These areas are also burdened with various types of human activities [117]. Kim et al. [118] reported similar findings from South Korea, where the deployment of OWF close to shore was limited due to social and environmental conflicts. In general, it can be expected that suitable areas for OWF are situated further away from the coast, if societal factors are included in the OWF planning. The role of ecological factors in driving OWF suitability depends on biogeographical and environmental characteristics of the marine area in question.

Various studies have used conservation areas as the main ecological constraining factor in OWF suitability analyses [43]. This suggests that areas outside the conservation areas are available for siting OWF. However, marine protected areas are often designed to protect a certain threatened species or habitat, rather than ecosystem functions or biodiversity. This was highlighted by a recent spatial prioritization study, which showed that marine protected areas overlook a large fraction of biodiversity hotspots [72]. The ecological component in the present analysis uses underwater marine biodiversity data from over 140 000 surveyed sites. Taxonomically rich and functionally important areas were recognized and considered in planning (un)suitable areas for OWF. Although such biodiversity rich areas are not necessarily officially protected, in spatial planning such areas could be marked as unsuitable for OWF.

The present analysis provides maps and quantitative information that can support decisions around marine zoning and wind farm placement in Finland. Marine areas that have recently been reserved for OWF development were also evaluated. It was concluded that the currently planned areas are overall well suited for wind power according to the present analysis (Fig. 5 and Table 2). On the other hand, proposed areas in the Bothnian Bay (planned areas e, f, h and i in Fig. 5, Table 2) show potentially high environmental impacts, as shown by the somewhat high biodiversity feature densities (>1,0) in these areas (Table 2). Having priority maps and quantitative information at hand may facilitate discussion and increase the transparency and societal acceptability of decisions. Sinclair et al. [119] found that the existence of spatial prioritizations alone could reduce environmental impacts as developers tended to avoid areas of high ecological priority, possibly to avoid complications during the permitting process. From a viewpoint of a wind power developer or a spatial planner, the present results provide a useful framework for discussions with stakeholders when planning new OWF. The analysis variants also support investigation of OWF from multiple perspectives, for instance with the help of the conflict map (Fig. 4).

The present work is significantly different from prior studies concerning ecologically informed spatial planning for OWF. One typical approach is utilization of standard GIS operations to map wind power potential. For example, Aydin et al. [120] developed many layers each describing the satisfaction of an individual criterion and these layers were then aggregated into an overall satisfaction degree, which was further utilized together with the wind potential map of Turkey. Pınarbaşı et al. [121] used Bayesian belief networks to integrate the technical, economic, environmental and social dimensions of wind farm feasibility. Bayesian belief networks create conditional probabilities, in this case of the suitability of a location for a wind farm, by integrating quantitative or semi-quantitative data and expert judgment, which is most applicable in relatively data limited situations. Another, rather common approach is the coupling of multi-criteria decision frameworks (e.g. analytical hierarchy process) to GIS [61,66,67]. Specific tools supporting spatial decisions are rarely used in OWF siting, although they would bring methodological advantages. For instance, connecting decision frameworks to GIS or thresholding spatial layers into suitable/unsuitable are not needed. A couple of examples do exist of the use of spatial conservation prioritization in the context of wind power. Winiarski et al. [70] used the Zonation software, which also was used here, to identify areas suitable for wind power that would not substantially conflict with the distributions of marine birds. Santangeli et al. [122] used Zonation to look at synergies and trade-offs between biodiversity conservation and expansion of renewable energies, including wind power. Göke et al. [123] used the target-based systematic conservation planning tool, Marxan, for the identification of optimal wind power sites in a pilot site in the Western Baltic Sea. Compared to this study, these works are much simpler in data and consequently also in analysis structure. In the present analysis, as a novelty, opposing and supporting factors (154 spatial layers) for OWF planning are integrated, in a spatial prioritization context, and cover 81 500 km^2.

All analyses can be improved, including this one. One interesting possibility is potential gains for particular species. It has been proposed that marine wind farms can actually provide benefits to some species, e.g. by acting as artificial reef habitats, providing shelter, and reproduction grounds for fish, or by acting as fisheries no-take zones with possible spill-over effects [39,87,124,125]. For example, coarse rock beds laid around foundations could provide new spawning grounds for Baltic herring assuming that the currents and the overall eutrophicated state of the Baltic Sea environment do not complicate spawning. Such benefits were not accounted for here, but analysis could be easily rerun with updated information, if quantitative data on the effects of wind turbine foundation types on fish reproduction, as well as fishing opportunities, were available.

The societal layers used in this study represent human landscape use broadly in terms of where people live, spend their free time and derive their income. However, spatially explicit information on important

Table 2
Characterization of potential large-scale wind farm sites, their mean priority ranks and feature densities for biodiversity, societal factors, economy and restrictions.

Site ID	Area (km^2)	Mean priority rank (%)	Feature density				
			All	Economy	Society	Biodiversity	Restrictions
Potential sites for offshore wind farms							
1	25	91,40	0,26	1,08	0,14	0,27	0,00
2	25	86,90	0,87	0,27	0,07	0,25	0,02
3	25	83,50	1,07	1,08	0,28	1,23	0,00
4	100	82,40	0,22	2,16	0,71	0,83	0,00
5	25	94,90	0,32	0,27	0,07	0,08	0,00
6	100	95,30	0,23	0,54	0,14	0,24	0,00
7	354	91,00	0,15	0,61	1,29	0,23	0,00
8	227	91,00	0,14	0,59	1,19	0,28	0,00
9	100	92,20	0,21	0,54	0,11	0,21	0,00
10	361	84,6	0,17	0,60	1,27	0,27	0,00
11	25	95,60	0,38	0,27	0,04	0,11	0,00
12	25	87,2	0,32	0,27	0,07	0,07	0,01
13	25	84,70	0,73	1,08	0,14	0,86	0,00
14	25	78,70	0,26	1,08	0,14	0,27	0,00
15	100	83,20	0,28	2,16	0,57	1,18	0,00
Existing offshore wind farms							
16	5	74,50	2,04	4,30	3,39	1,81	0,00
Planned offshore wind farms							
a	39	60,20	0,85	1,37	0,63	0,29	0,00
b	60	72,60	0,84	0,90	0,29	0,43	0,00
c	58	54,50	0,96	0,92	0,30	0,70	0,00
d	134	92,20	0,40	0,60	0,21	0,41	0,00
e	44	25,80	0,36	0,61	0,40	1,58	0,00
f	64	97,00	0,28	0,42	0,17	1,33	0,00
g	163	74,30	0,55	0,83	0,17	0,61	0,00
h	87	92,80	0,36	0,62	0,25	1,32	0,00
i	17,0	14,8	2,32	3,18	1,46	2,48	0,00

places and place attachment of local people, and the use of areas by the tourism sector are missing, and could be complemented by surveys or social media data [126]. A special case is tourism, for which separate layers were included indirectly: information of summer cottages, national parks, boating lanes, boating intensity, and services are linked to where people, including tourists, spend time. Hence, if it is possible to situate OFW away from the presently modelled societal sea uses, the tourism and other similar activities should not be disturbed by OWF. It should be noted that the current literature tends to treat tourists as a homogenic group, focused mostly on the disturbing effects of OWF [16,127,128]. That might be the case especially in areas where the aesthetic value of the landscape is the sole motivation of recreational visits. However, attitudes of tourists towards OWF differ, and are shaped by values and preferences [129,130]. OWF may also provide new opportunities for the tourism sector, as OWF could serve as attractants, places people want to visit [131].

Another factor ignored was regional politics, including real estate tax, which goes beyond the scope of this analysis. Each wind farm is a unique business case and general suitability does not guarantee overall feasibility for the specific case. For example, seabed substrate may become a deal breaker if site-specific drill surveys find that the seabed profile differs from expected. Currently, there does not exist seabed substrate data that covers deeper layers of the seabed. Thus, further exploration would be needed in areas recognized as suitable for OWF. Further along the potentially years-long planning process, comprehensive environmental impact assessments, zoning plans, and permits are needed for thorough investigations of the potential impacts of a larger OWF on its surroundings. Even though numerous environmental datasets are available for the development process, rather extensive field studies and analyses are still required by the authorities prior to permitting.

Finally, a standard clause in spatial prioritization studies is that base data layers could be improved either by adding layers, or by improving the resolution and quality of layers. In this study, the breadth and quality of data is high, and the resolution more than adequate. OWF spread easily over 100 km^2, and large ones cover hundreds of square kilometers. Fine-scale, local nature hotspots can possibly be protected with careful turbine placement. Thus, going beyond 100 m would add little advantage. Given the number and quality of layers included already, one should not expect that changes in individual layers or the addition of a few new layers would drastically change the character of the results [132].

The wind energy sector develops fast, and today's technologies become outdated quickly. Offshore turbines grow in size and power ratings, which opens new opportunities for wind energy developers. The levelized cost of energy is expected to decrease remarkably in the future, due to turbine technology and marine operations resulting in lower costs per installed megawatt. Considerably deeper and more expensive sites further away from the coast might become acceptable when revenue per turbine increases along with more powerful turbines. Transition to subsidy-free, completely marked-based offshore wind projects is still ongoing. Due to high construction and operating costs in the deep open sea, first market based OWF are likely to be sited comparatively near the coastline. In the future, when offshore wind turbines exceed a power rating of some 20 MW, market-driven projects may be able to utilize also the sites further away from the port and power transmission infrastructure.

5. Conclusions

This study provides a generic approach for well-informed analysis of offshore wind farms (OWF) development potential when conflict resolution between biodiversity, societal factors and economic profits is needed. It also facilitates the use of spatial prioritization methods in marine spatial planning and impact avoidance applications and provides an approach for OWF suitability analyses.

- Spatial prioritization methods were adapted to provide a pragmatic way for integrating high-dimensional spatial data, which represent ecological, societal (people, maritime sectors) and economic factors in the planning of offshore wind power

- A generic approach for integrating opposing and supporting factors in the OWF development are provided, in a spatial prioritization (Zonation) context
- Over 150 spatial data layers were developed at a 100 m resolution, for well-informed suitability analysis of offshore wind farms, across the Finnish marine areas (81 500 km^2)
- When only one opposing/supporting criterion was considered, suitable areas for OWF changed from closer to shore in the economics-only analysis to further away in societal- and ecological-only analyses
- Areas most suitable for OWF were identified based on integrated spatial prioritization. When all factors were included, economically highly profitable OWF solutions could be found that would cause little disturbance to biodiversity and the society. The analysis also shows areas with high environmental impacts and/or low societal acceptance, which would hence be poorly suited for OWF.
- A novel method was developed for the visualization of conflicts and synergies between biodiversity, society and deployment of offshore wind power. This visualization can facilitate constructive dialogue between stakeholders in a spatial planning context.
- Existing and planned offshore wind farms were evaluated based on the results of this study. Overall, these areas were well suited for wind power, with the exception of a couple of areas with comparatively high impacts on biodiversity.
- The proposed approach is replicable elsewhere in the world, and structurally suitable for the planning of impact avoidance and conflict resolution, including other forms of construction or resource extraction.

Economic, social and environmental dimensions need to be carefully addressed in sustainability transformation. Results such as presented here can inform policy making, investments into offshore wind energy, and sustainable use of the sea areas.

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Author credit statement

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Data availability

Datasets related to this article can be found at DOI 10.5281/zenodo.5838495, an open-source online data repository hosted at Zenodo.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112087.

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