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Linking Marine Ecosystem Services to the North Sea's Energy Fields in Transnational Marine Spatial Planning

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Abstract: Marine spatial planning temporally and spatially allocates marine resources to different users. The ecosystem approach aims at optimising the social and economic benefits people derive from marine resources while preserving the ecosystem's health. Marine ecosystem services are defined as the benefits people obtain from marine ecosystems. The aim of this study is to determine which interrelations between marine ecosystem services and the marine energy industry can be identified for use in transnational marine spatial planning exemplified in the North Sea region. As the North Sea is one of the busiest seas worldwide, the risk of impairing the ecosystems through anthropogenic pressures is high. Drawing on a literature-based review, 23 marine ecosystem services provided by the North Sea region were defined and linked to seven offshore energy fields comprising oil and natural gas, wind, tides and currents, waves, salinity gradients, algal biomass, and geothermal heat. The interactions were divided into four categories: dependence, impact, bidirectional, or no interaction. Oil and natural gas, as well as algae biomass, are the fields with the most relations with marine ecosystem services while waves and salinity gradients exhibit the least. Some marine ecosystem services (Conditions for Infrastructure, Regulation of Water Flows, and Cognitive Development) are needed for all fields; Recreation and Tourism, Aesthetic and Cultural Perceptions and Traditions, Cognitive Development, and Sea Scape are impacted by all fields. The results of this research provide an improved basis for an ecosystem approach in transnational marine spatial planning.

Keywords: ecosystem approach; marine energy; blue growth; environmental management

1. Introduction

For centuries, marine environments and their natural resources have been used by humans for multiple benefits, such as fishing, recreation, and other cultural activities. Simultaneously, oceans are decisive for climate regulation as they (emit and) absorb greenhouse gases, such as carbon dioxide [1]. The ostensible vastness of the ocean has made it appear to be a limitless source of these benefits. Hence, marine businesses have been expanding for decades. The European Union has coined the concept of Blue Growth [2] which not only refers to the increase in marine sectors, but also to a long-term strategy promoting sustainable development. The North Sea, a marginal sea of the Atlantic Ocean in the north-west of Europe, has been experiencing a large expansion of marine industries, such as the exploitation of energy resources. Since the 1960s, the extraction of crude oil and natural gas has been an important economic activity in the North Sea [3]. In recent years, technologies have been under development to harness marine renewable energy resources including wind, waves, tidal streams and currents, salinity gradients, algal biomass, and geothermal energy [4–7]. With more than 3500 installed wind turbines with grid connection, providing over 12,600 MW capacity [8], offshore wind turbines are the most commonly used renewable energy technology. While oil and natural gas platforms relate to the location of subsurface reservoirs, renewables installations can be placed more widely.

However, pressures from anthropogenic activities may impair the condition of marine ecosystems and, with that, the benefits humans gain from them [9,10]. Marine spatial planning (MSP) allocates marine resources spatially and temporally to (conflicting) anthropogenic uses of the marine environment while preserving the ecosystem [10–14]. MSP effectively integrates scientific knowledge and geospatial information into decision-making. Conflicts between ecological, social, and economic interests are minimised by identifying areas that are useful for each use [15,16]. MSP becomes a transnational challenge when the marine space is divided into several sovereign territories, as is the case in the North Sea.

Since the 1990s a shift towards a holistic inter- and transdisciplinary planning and management approach has occurred. The ecosystem approach (EA) was shaped by the Convention on Biological Diversity [17]. The term ecosystem refers to all biological, physical, and chemical processes of the environment without specifying any particular spatial scale [17]. The EA is embedded in the concept of sustainability and considers the interactions between multiple cultural, economic, technical, and ecological aspects on different temporal and spatial scales [18–20]. The natural capacity of the ecosystem sets the limits to the central goal of optimising human benefits [11,19,21–24]. Thus, the concept helps to close the conceptual gap between human preferences and natural marine ecosystems by linking the ecosystem state to anthropogenic benefits [25].

The European Marine Strategy Framework Directive [26] mandates member states of the European Union to provide marine spatial plans by March 2021. The Marine Spatial Planning Directive [11] recommends the application of the EA for sustainable use of marine resources. At the Fifth International Conference on the Protection of the North Sea in 2002 in Bergen, Norway, the North Sea states committed themselves to implementing the EA [27]. Although the North Sea states, in general, are frontrunners in implementing MSP, not all countries are equally advanced.

The concept of marine ecosystem services (MarES) is an approach capable of operationalising the EA in MSP. In line with the Millennium Ecosystem Assessment [14], this study defines ecosystem services as the benefits people obtain from ecosystems. MarES can be used knowingly or subconsciously [28] and include physical as well as emotional benefits connected with a sense of well-being that results from experiencing the natural ecosystems. Our literature review revealed several different definitions and categorisations of ecosystem services, which indicates a lack of conceptual clarity. This discrepancy must be acknowledged when interpreting the respective study results. Boyd and Banzhaf [29] and Fisher et al. [13], for example, criticise that ecosystem services are not identical with benefits but rather link the natural components of the ecosystem and anthropogenic uses. Nevertheless, for the purpose of this study, the applied definition is expedient as MarES are not valued economically and tangible benefits are needed in order to identify interactions between anthropogenic uses and the environment. Furthermore, Wallace [30] points out the distinction between goods and services in everyday language. However, in this research, ecosystem services include goods (e.g., Food Supply) and services (e.g., Coastal Protection) as both categories refer to benefits people derive from ecosystems.

As, hitherto, MarES have rarely been integrated into MSP [25], this study concludes that they are a subject of interest but need further definition. The present research aims at improving the understanding of MarES in the context of offshore energy production and at providing a basis for a sustainable management of manifold marine uses. This study intends to answer the following research question: Which interrelations between the marine energy industry and marine ecosystem services can be identified in order to enhance transnational MSP in the North Sea region?

2. Materials and Methods

2.1. Investigation Area

The North Sea is located between Norway, Sweden, Denmark, Germany, the Netherlands, Belgium, and Great Britain, and is connected to the Norwegian Sea in the north, to the Baltic Sea in the east, and to the English Channel in the south-west. Despite an extent of approximately 570,000 km^2, the mean depth of the shelf sea is only 90 m [31]. Among other factors, the shallow water allows exploitation of different energy sources in the entire North Sea, even if platforms are needed.

Characterised by the boreal biogeographic zone, the North Sea is located in a temperate climate under a strong influence of oceanic and atmospheric circulations coming from the west [32]. An anticlockwise circulation mixes salt water from the Atlantic Ocean with freshwater inputs from rivers and land runoff [32]. The North Sea area is largely influenced by tides and composed of various marine landscapes including mudflats, sandbanks, estuaries, and fjords. The seabed is constituted mostly of sand and mud. Rocky areas support the colonisation of kelp forests as well as bivalves. Around 230 recorded species of fish, more than 10 million seabirds and several marine mammals inhabit the North Sea. The Wadden Sea—a UNESCO World Heritage site stretching along the coasts of Denmark, Germany, and the Netherlands—is an especially productive area and an important spawning ground for many species. Simultaneously, the North Sea coasts are densely populated and highly industrialised with two of the world's largest ports—Hamburg and Rotterdam—situated on its coasts [33].

As one of the busiest seas worldwide on the one hand, and an extremely productive and diverse ecosystem on the other hand, the North Sea provides an ideal location for investigating the interactions between human activities and ecosystems.

2.2. Marine Ecosystem Services

Since the evaluation of ecosystem services has focused on terrestrial ecosystems in the past, the number of publications featuring MarES is still limited. The MarES classification systems from Atkins et al. [34], Beaumont et al. [35], Böhnke-Henrichs et al. [25], Hattam et al. [18], and Liquete et al. [36] were considered most relevant for the scope of this research because they included a comprehensive overview of ecosystem services in a marine environment. Except for Böhnke-Henrichs et al. [25] and Hattam et al. [18], all articles defined ecosystem services differently, although single MarES were named identically. These discrepancies were considered in contrasting the classifications (see Supplementary Materials). Since this article considers technologies for energy production other than those of the five articles named above, a new list of MarES including definitions was compiled (Table 1). MarES meeting the following criteria were included:

- MarES and coastal ecosystem services that have a strong connection to marine ecosystems;
- MarES relevant to the North Sea area;
- MarES relevant to the (offshore) production of energy;
- Direct MarES that can be enjoyed immediately and indirect MarES that need to be coupled with other forms of capital.

Table 1. Definition of relevant marine ecosystem services. The first column lists the names of the numbered marine ecosystem services (MarES); the second column provides definitions of each of the MarES.

	Name	Definition
1	Food Supply	The marine flora and fauna extracted from unmanaged environments or aquacultures that are used for human consumption.
2	Water Supply	The marine water (i.e., saline, brackish, and freshwater) that is abstracted from the water column and aquifers for human consumption and for use in industrial and economic activities.
3	Genetic Resources	The genetic material from marine organisms that is extracted for nonmedical, nonfood purposes.
4	Medicinal Resources	The material that is extracted from or used in the marine environment for its ability to provide medicinal benefits.
5	Raw Materials	The marine material that is extracted for human nonfood uses, excluding those covered by Services 3 and 4.
6	Fossil Hydrocarbon Resources	The fossil organic materials exploited from marine subsurface reservoirs.
7	Renewable Energy	The use of the marine environment for the generation of renewable energy.
8	Storage	The use of marine subsurface natural fractures and pores and artificial structures for storage purposes.
9	Conditions for Infrastructure	The use of marine environments for the foundation and protection of infrastructure.
10	Transportation	The use of waterways for commercial shipping.
11	Weather Regulation	The regulation of local weather conditions by marine ecosystems.
12	Air Purification	The regulation of the concentration of physical and chemical substances in the lower atmosphere by marine ecosystems.
13	Climate Regulation	The regulation of the concentration of climate-active gases by marine environments.
14	Water Purification	The removal of physical, chemical, and biological substances from seawater by marine ecosystems.
15	Nutrient Cycling	The natural cycling processes leading to the availability of nutrients in seawater that produce organic matter.
16	Coastal Protection	The protection of humans and the built environment against extreme events, such as storm floods and coastal erosion.
17	Regulation of Water Flows	The contribution of marine ecosystems to the maintenance of localised coastal current structures.
18	Biological Self-Control	The contribution of marine ecosystems to the maintenance of population dynamics, resilience through food web dynamics, disease and pest control.
19	Lifecycle Maintenance	The marine habitat that marine organisms and communities provide for a healthy and diverse environment, including viable gene pools.
20	Recreation and Tourism	The opportunities that marine ecosystems provide for relaxation and leisure or amusement.
21	Aesthetic and Cultural Perceptions and Traditions	The individual and societal associations with and emotional responses to the marine environment itself in traditions, art, and religion.
22	Cognitive Development	The generation of knowledge and technological development resulting from researching marine environments.
23	Sea Scape	The emotional benefit attached to the marine environment without physical use.

2.3. Marine Energy Fields

The second part of the present study focused on interactions between the different energy fields and MarES. This research included all offshore activities as well as coastal energy productions that directly interact with MarES (Table 2). The term energy refers to electricity as well as to other materials that are used to generate either electricity or heat. This study covers a planning horizon stretching until 2030. The process of marine energy production is taken into account in the description of marine energy fields. Additional offshore infrastructure, onshore activities, and possibilities of energy storage and reductions of energy consumption due to the access to MarES are not considered.

Table 2. Overview of reviewed offshore energy fields. For each field (rows), information on the exploited resource, technology, output, and innovation status in the North Sea is provided (columns).

Energy Field	Exploited Resource	Technology	Output	Innovation Status
Offshore oil and natural gas	Crude oil and natural gas from subsea reservoirs	Exploratory drilling e.g., [7,37] Exploitation of one or several well(s) using bottom-fixed or floating offshore platforms, see [7,38,39]	Crude oil, natural gas	Proven technology
Offshore wind energy	Kinetic energy of air	Turning of rotors (typically 95 m above sea level) by wind Bottom-fixed or floating offshore platforms, see [40–44]	Electricity	Proven technology
Tidal and ocean current energy	Potential and kinetic energy of tides and ocean currents	Tidal barrages and lagoons Dams built across estuaries or circularly in open water [15] Three operating schemes: ebb generation, flood generation, ebb and flood generation (two-way generation) Most commonly, ebb generation traps water at high tide and then releases it to drive turbines Tidal stream and current power generators Submerged rotors [45]	Electricity	Development phase, operational
Wave energy	Kinetic energy of waves	Multiple concepts, e.g., point absorber, attenuator or linear absorber, terminator [40,46–48] A stable central part that intercepts the waves and an attached mobile part that moves relative to the central part	Electricity	Development phase, operational
Salinity gradient energy	Different salt concentrations of river water and seawater at river mouths	Abstraction and discharge of fresh and saltwater Multiple concepts Membrane-based techniques relying on osmosis: *pressure-retarded osmosis* (PRO) [49,50] and *reverse electrodialysis* (RED) [5,51]. *Capacitive mixing* (CapMix) [49,52]	Electricity	Research and development phase
Algal biomass energy	Marine algae, especially kelp, brown phaeophyte macroalgae [53]	Harvest of natural stocks or longline cultivations [54,55] using mowers and nets or skimmer boats. Cleaning of seawater from other algae species and contaminants Additional fertilisation with deep seawater or nutrient-rich effluents from fish farms possible [6,56]	Algal biomass	Proven technology, but rare
Offshore geothermal energy	Earth's interior heat from underground reservoirs	Reuse of disused offshore oil and natural gas platforms above high-pressure and high-temperature reservoirs to extract hot gases or liquids [57,58]	Electricity	Research phase

2.4. Interactions of MarES and Marine Energy Fields

While several studies are available on how a respective energy field impacts on its environment, e.g., [59], research on MarES that are needed for an energy field to function is limited, e.g., [19]. The classification of the interactions is based on existing literature and on the description of the marine energy fields (Table 2). The determined relationship referred to all affected MarES during the whole (offshore) lifecycle of the energy plant. It included normal functioning but excluded extraordinary circumstances as well as potential onshore activities during manufacturing and disposal of any materials. The spatial scale of an interaction is limited to the close surrounding of an energy plant or energy farm. The present research reviewed only direct impacts and did not consider cascades that may increase an impact's temporal and spatial extent. Within the scope of this article it was not possible to describe all interactions in detail. For further information, please refer to the cited literature.

3. Results

The determined interactions between each offshore energy field and MarES, respectively, provided specific use profiles for each energy field (Table 3). The following paragraph highlights examples for such interactions.

Offshore energy fields requiring platforms (cf. Table 2) introduce hard substrate into the environment. This artificial reef influences the species composition which directly impacts on the Food Supply, Water Purification, Nutrient Cycling, Biological Self-Control, and Lifecycle Maintenance MarES. The fields using oil and gas, salinity gradients, and geothermal energy need (sea)water for cooling or general functioning, i.e., the MarES Water Supply. Additionally, the evaporation of cooling water impacts on the Weather Regulation. All marine energy fields depend on the provided Condition for Infrastructure for foundation or mooring. All offshore fields interact bidirectionally with the Transportation MarES as they rely on boats during construction and maintenance but also locally restrict shipping routes. Offshore energy plants deploy a certain hydrodynamic regime and the technology needs to be adjusted to prevailing water depths and speeds. Therefore, all offshore fields depend on the natural Regulation of Water Flows. The fields using tides and currents, waves, and salinity gradients also impact on this MarES as well as on Coastal Protection by influencing currents and sedimentation patterns. All social services—Recreation and Tourism, Aesthetic and Cultural Perceptions and Traditions, Cognitive Development, and Sea Scape—are impacted because the exploitation of marine energy influences the view people have on the marine environment. An emerging offshore energy field may add a new facet to this image or evoke social resistance. Furthermore, the implementation of new technologies relies on and advances Cognitive Development.

Table 3. The interactions between the energy fields (columns) and the respective marine ecosystem services (MarES) (rows). The table displays the energy fields that use offshore oil and natural gas, offshore wind, tides and ocean currents, waves, salinity gradients, algal biomass, and offshore geothermal energy. Interactions are divided into four categories which are indicated by the colouring of each table element: Dependence (black) means that an energy field needs the respective MarES to function; impact (light grey) indicates a direct, immediate positive or negative influence of the energy field on the MarES that alters its quality or quantity; bidirectional interaction (dark grey) relates to both a dependence and an impact, while no interaction (white) refers to neither. The interactions may counteract or amplify each other. The determination of the interactions is based on the following references, respectively. The references are allocated to each field; the numbers represent the MarES.

MarES	Energy Field	Oil and Natural Gas	Wind	Tides and Currents	Waves	Salinity Gradient	Algal Biomass	Geothermal Energy
1	Food Supply	░	░	░			░	░
2	Water Supply	■		▓		▓		■
3	Genetic Resources						▓	
4	Medicinal Resources							
5	Raw Materials	░	░	░	░		▓	░
6	Fossil Hydrocarbon Resources	▓						
7	Renewable Energy	░	▓	▓	▓	■		▓
8	Storage	▓						▓
9	Conditions for Infrastructure	■	■	■	■	■	■	■
10	Transportation	▓	▓	▓	▓		▓	▓
11	Weather Regulation	░	▓			░	▓	░
12	Air Purification						▓	
13	Climate Regulation						░	
14	Water Purification	░	░	░		▓	▓	░
15	Nutrient Cycling	░	░	░		░	▓	░
16	Coastal Protection			░	░			
17	Regulation of Water Flows	■	■	▓	▓	▓	▓	■
18	Biological Self-Control	░	░	░			▓	░
19	Lifecycle Maintenance	░	░	░			▓	░
20	Recreation and Tourism	░	░	░	░	░	░	░
21	Aesthetic and Cultural Perceptions and Traditions	░	░	░	░	░	░	░
22	Cognitive Development	▓	▓	▓	▓	▓	▓	▓
23	Sea Scape	░	░	░	░	░	░	░

Offshore oil and natural gas—own assessment: 1, 3, 4, 5, 6, 7, 8, 9, 11, 15, 16, 17, 18, 19, 20, 21, 22, 23; OSPAR [32], Orszulik [60]: 2, 12, 13, 14; Hilyard [7]: 14; **Offshore wind energy**—own assessment: 2, 3, 4, 6, 8, 12; Burkhard et al. [61]: 15; Busch et al. [62]: 1, 5; Hau [43]: 1, 5, 7, 9, 10, 11, 17, 18, 21; Köller [63]: 18; Lange et al. [19]: 3, 4, 9, 13, 14, 16, 18, 20, 22, 23; Langhamer [64]: 1; Lynn [41]: 1, 5, 18; Mangi [65]: 1, 5, 15, 18, 19, 21; Manwell et al. [66]: 18, 21; OSPAR [67]: 1, 5, 9, 18; Shields [68]: 1, 9, 15, 17, 18, 19; Thomsen et al. [69]: 18; Thomsen [44]: 7, 9, 11, 17, 18; **Tidal and ocean current energy**—own assessment: 2, 3, 4, 5, 6, 7, 8, 11, 12, 13; Bedard et al. [5]: 15, 17, 18, 19; Boyle [45]: 1, 10, 15, 16, 17, 18, 19; Haslett et al. [70]: 1, 10, 14, 15, 18, 19, 20, 21, 22, 23; Kadiri et al. [48]: 1, 9, 10, 15, 16, 17, 18, 19; Langhamer [64]: 1; Leslie and Palmer [47]: 1, 10, 15, 17, 18, 19, 20; **Wave energy**—own assessment: 1, 2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23; Bedard et al. [5], Boyle [45], Drew et al. [46]: 9, 10, 16, 17; Shields [68]: 1, 9, 15, 17, 18, 19; **Salinity gradient energy**—own assessment: 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16, 18, 19, 20, 21, 22, 23; Helfer et al. [50], Staalstrøm and Gitmark [71]: 2, 14, 15, 17; Alvarez-Silva et al. [72]: 17; **Algal biomass energy**—own assessment: 2, 3, 4, 6, 7, 8, 11, 12, 13, 16, 22; Bedard et al. [5]: 1, 5, 9, 10, 15, 18, 19; Burton et al. [56]: 20, 21; Copping et al. [15]: 1, 5, 14, 15, 17, 18, 19; Gill [73]: 1, 15, 18; Inger et al. [74]: 1, 5, 15, 17, 18, 19; Thomsen et al. [69]: 18; **Geothermal energy**—own assessment.

4. Discussion

4.1. Relations

The study has revealed insights into the relations of MarES and the marine energy fields. This study has identified distinct interaction profiles for each marine energy field (Table 3). All considered energy fields depend on the ecosystem services Conditions for Infrastructure, Regulation of Water Flows, and Cognitive Development. As all potential offshore energy uses need these MarES in order to function, one energy field's activities may interfere with another field's ability to access the needed MarES. To mediate conflicts that may emerge, effective management is especially important. All energy fields impact on Recreation and Tourism, Aesthetic and Cultural Perceptions and Traditions, Cognitive Development, and Sea Scape. The presence of offshore energy plants thus indicates possible cultural implications of energy production that need to be considered in management plans. These findings comply with those of Lange et al. [19] who ascertained that cultural implications are likely to be delimited to a regional scale in the North Sea. When an energy field impacts the structure and functions of the ecosystem, the provision of the MarES may be compromised, cf. [19]. The consequences of such a degradation are uncertain and may hinder the operation of other energy fields and uses. Those MarES that show bidirectional interactions with multiple energy fields, such as Transportation and Regulation of Water Flows, need to be monitored closely and managed appropriately. In these cases, several fields depend on a certain MarES while also possibly changing its state and availability. The erection of a marine energy farm may, for example, reduce available shipping routes and change current patterns while also depending on the provision of these, cf. [5,43,45–48]. The Genetic Resources, Medicinal Resources, Fossil Hydrocarbon Resources, Storage, Air Purification, and Climate Regulation MarES are needed or impacted on by a maximum of two energy fields. A rivalry over these MarES is, therefore, less probable. All fields needing foundations on the seafloor impact MarES the most. The physical conditions are altered but so, too, are the biological and chemical environment.

The number of determined interactions with MarES per field does not differ strongly (Figure 1). Renewable energies do not necessarily have a smaller environmental impact than the exploitation of fossil energy resources.

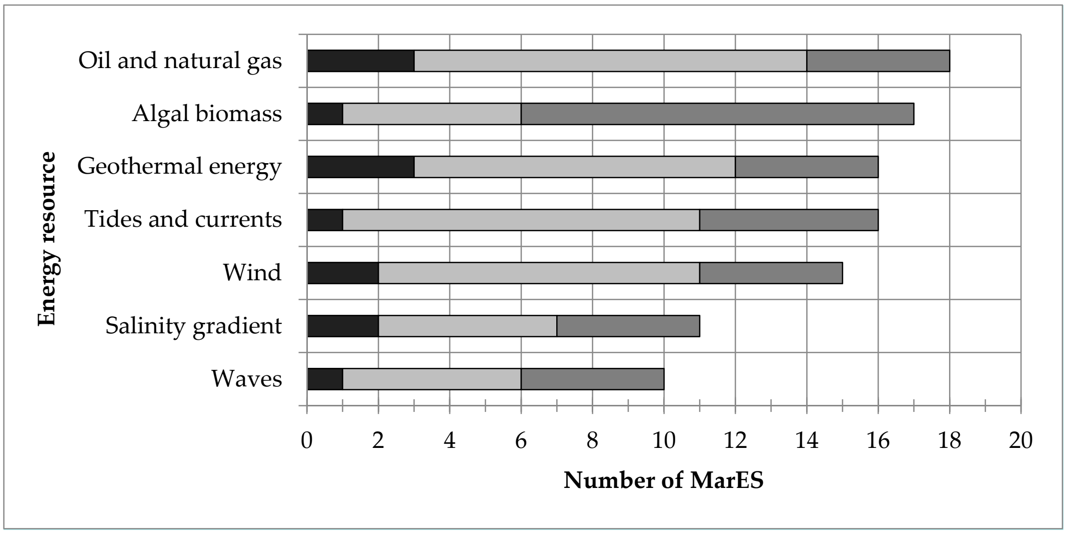

Figure 1. Overview of the number of marine ecosystem services (MarES) each energy field interacts with. The figure shows the energy fields that use offshore oil and natural gas, offshore wind, tides and ocean currents, waves, salinity gradients, algal biomass, and offshore geothermal energy. Additionally, a field's dependence (black) and impact (light grey) on MarES as well as bidirectional interactions (dark grey) are indicated.

With respect to renewable energies, the algal biomass energy field is connected to the highest number of MarES as it is based on growing biomass in the marine environment, while the wave and salinity gradient energy fields interact with the least number of MarES. The number of impacted MarES is especially small compared to the other fields. However, it needs to be noticed that the number of interactions does not necessarily correlate with the intensity of the interaction.

Ecosystem health is a prerequisite for the provision of MarES and, thus, for all marine energy fields. Energy fields and MarES with manifold interactions need to be managed especially carefully to prevent a deterioration of the ecosystem's health.

4.2. Limitations

The innovation status of each energy field is characterised by a varying availability of data and literature. The data available on salinity gradient energy and geothermal energy is especially limited. Liquete et al. [36] ascertained that few studies provide unbiased assessments of MarES. The Food Provision, Water Purification, Coastal Protection, Lifecycle Maintenance, and Recreation and Tourism MarES are best researched while the evidence on the other MarES is less profound [36]. The interactions were neither mapped and evaluated geographically nor distinguished in their intensity. Each field was assessed independently, and the determined interactions do not include synergies or co-uses of several energy production technologies. Copping et al. [15] ascertained that data and resources were the main limiting factors for implementing MSP. Therefore, it is important to monitor and study marine ecosystems and the interactions between biota, abiotic components, and human activities further in order to provide applicable information for MSP [23,27,75]. By proposing an assessment of all MarES within the used classification, this study applies a more comprehensive viewpoint and supports further evaluation of trade-offs between different marine energy fields.

It is important to notice that the interactions between offshore installations and MarES vary temporally and spatially. The different phases of an offshore activity, i.e., exploration, installation, exploitation, and decommissioning, use and affect a different set of MarES; see, e.g., [76]. Offshore installations that cannot be seen from the shore will have a smaller effect on social MarES than installations that collide with coastal activities. The interactions also depend on the physical characteristics of the installations which vary even within each subfield. The offshore oil and gas and offshore wind energy fields, for instance, may use fixed or floating platforms. For a fixed platform, the seabed must be prepared and therefore disturbed, while a floating platform affects the ground less. With the established interactions between the energy field and MarES, the design of the energy plants can be optimised to minimise adverse effects. In marine environments with their vast spaces and fluid boundaries, the location at which MarES are provided and enjoyed may differ from or exceed the planning area. Furthermore, cause and effect of an impact may be distant in space and time [9]. For instance, offshore energy plants function as a reserve area for fish to develop [41,43,62,65]. Consequently, fisheries may benefit from greater fish abundance in the North Sea even though the available fishing grounds are reduced. Aesthetic and cultural MarES are especially difficult to delimit.

This research needed to simplify the complexity of marine ecosystems which are characterised by different and overlapping temporal and spatial scales as well as often nonlinear causalities and delayed responses to pressures [22,77]. The established interactions need to be characterised more specifically concerning their intensity, spatial and temporal extent, interdependence, and exact nature, i.e., whether they are beneficial or harmful to the environment [5]. Fisher et al. (2009) advocate the need to link classifications of ecosystem services to policy and site-specific circumstances. To apply the results of this study to MSP, they need to be adjusted to the respective technology, society, state, institution, and ecosystem. Each management process using the EA is uniquely characterised by the involved stakeholders and their interests as well as by the specific ecosystem. Social preferences, economic interests, and site-specific data, such as wind and wave force and direction, currents, sea bottom characteristics, and biological data, need to be considered [11,75]. In order to manage the complexity of marine ecosystems and to incorporate newly gained knowledge, the EA requires adaptive management [17].

4.3. Policy Implications and Transnational MSP

Marine management applying the ecosystem approach needs information on the interplay between human activities and marine ecosystems. This study determines profiles for seven marine energy fields describing their interaction with MarES. As these profiles partly overlap, integrated policies and holistic management considering all offshore activities are crucial. However, clashes of different policies, values, and viewpoints (for instance, an anthropocentric versus a biocentric view) can hinder an outcome that is beneficial to all stakeholders. Integrating the EA into MSP can facilitate communication between stakeholders, planners, and politicians, and thereby optimise the benefits for all concerned parties [19]. International and interfield coordination and cooperation with the application of combined political targets are essential. In order for this collaboration to work, each country has to designate authorities responsible for the implementation of MSP [11].

The definition of ecosystem services used in this research is characterised by an anthropocentric view, i.e., the benefits humans obtain from the ecosystem. The EA applies this perspective to MSP while emphasising the importance of an ecosystem for maintaining these benefits. The MarES profiles depend on resources that are provided in a marine basin and its ecosystems at different locations. The zoning approach is an MSP concept that tries to realise the complexity of the system by assigning to each use a zone in which it can be performed. The determined relationships between MarES and the energy fields can be geographically allocated and mapped for MSP. By considering the dependence of each energy field on particular MarES and weighing the impacts of different uses, zones can be assigned to a field with high dependence and minimal impact on a particular ecosystem. Thus, the results of this study support MSP in identifying suitable locations in an entire basin in a transnational approach. Nevertheless, this zoning approach may cause problems when certain zones promise high energy yields for multiple offshore energy fields. Therefore, clear criteria need to be established that indicate the nature of the interactions and a sustainable usability of the marine space, and thereby regulate the distribution of zones.

5. Conclusions

This study has provided further evidence that MarES are essential to understanding the impacts marine energy exploitation has on marine environments and the North Sea basin in particular. The growing marine energy industry causes increasing anthropogenic influence on the marine environment and trade-offs connected with it. This study integrated 23 MarES in the North Sea basin into the context of offshore energy production and ascertained use profiles by determining the interactions between MarES and marine energy fields according to four categories. Our division of the offshore energy industry into seven energy fields provides links between societal issues of (i) climate change and the conservation of marine environments and (ii) innovation and economic benefits from marine realms. The transition from fossil to renewable marine energies implies more diverse and different modes of interaction of maritime use with MarES for energy purposes. Marine planning and ocean management should consider these various modes and the specific profile of each energy field. In particular, the profiles are supportive of surveying the subregions of a marine basin with respect to their provision and the vulnerability of key MarES. The determined interactions facilitate identifying areas that are adequate for each use so that conflicts between ecological, social, and economic interests are minimised. MSP needs to consider that interactions vary temporally and spatially and that cause and effect of an impact may be distant in space and time. The service-providing ecosystems of the North Sea basin are heterogeneously distributed and characterised by fluid boundaries. Thus, the sustainable and efficient management of marine energy requires a transnational approach in which all bordering states coordinate their political targets and cooperate if possible. The use profiles of the energy fields can facilitate communication between stakeholders, planners, and politicians, and promote the implementation of the ecosystem approach in transnational MSP.

An ecosystem approach to policy-making that considers human needs, as well as environmental aspects, is essential [34]. This study has identified relationships between the marine energy fields and MarES on a qualitative level. MSP should also consider quantitative aspects of current and future relationships. The adoption of the approach presented is likely to show similar results in other sea basins.

Supplementary Materials: The following table is available online at http://www.mdpi.com/2076-3298/5/6/67/s1. Table S1: Categorisation of relevant marine ecosystem services.

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