103. Floss HG, Yu TW (2005) Rifamycin-mode of action, resistance, and biosynthesis. Chem Rev 105(2):621–632
104. Kim W et al (2009) Rational biosynthetic engineering for optimization of geldanamycin analogues. Chembiochem 10(7):1243–1251
105. Bedin M et al (2004) Geldanamycin, an inhibitor of the chaperone activity of HSP90, induces MAPK-independent cell cycle arrest. Int J Cancer 109(5):643–652
106. Neckers L, Schulte TW, Mimnaugh E (1999) Geldanamycin as a potential anti-cancer agent: its molecular target and biochemical activity. Invest New Drugs 17(4):361–373
107. Delcour AH (2009) Outer membrane permeability and antibiotic resistance. Biochim Biophys Acta 1794(5):808–816
108. Mollmann U et al (2009) Siderophores as drug delivery agents: application of the "Trojan Horse" strategy. Biometals 22(4):615–624
109. Braun V et al (2009) Sideromycins: tools and antibiotics. Biometals 22(1):3–13
110. Ballouche M, Cornelis P, Baysse C (2009) Iron metabolism: a promising target for antibacterial strategies. Recent Pat Antiinfect Drug Discov 4(3):190–205
111. Wencewicz TA et al (2009) Is drug release necessary for antimicrobial activity of siderophore-drug conjugates? Syntheses and biological studies of the naturally occurring salmycin "Trojan Horse" antibiotics and synthetic desferridanoxamine-antibiotic conjugates. Biometals 22(4): 633–648
112. Borisova SA et al (2010) Biosynthesis of rhizocticins, antifungal phosphonate oligopeptides produced by *Bacillus subtilis* ATCC6633. Chem Biol 17(1):28–37
113. Vondenhoff GH et al (2011) Characterization of peptide chain length and constituency requirements for YejABEF-mediated uptake of Microcin C analogues. J Bacteriol 193(14):3618–3623

Aquaculture and Renewable Energy Systems, Integration of

Bela H. Buck[1,2,3], Gesche Krause[4]
[1]Biological Sciences – Marine Aquaculture, Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, Germany
[2]Marine Aquaculture for Sustainable Fisheries, Institute for Marine Resources (IMARE), Bremerhaven, Germany
[3]Maritime Technologies – Applied Marine Biology, University for Applied Sciences, Bremerhaven, Germany
[4]Leibniz Center for Tropical Marine Ecology (ZMT), Bremen, Germany

Article Outline

Glossary

Aquaculture Following the definition of the FAO [1, 2], *aquaculture* is the farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants with some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, and protection from predators. Specifically, *marine aquaculture*, also called *mariculture*, concentrates on aquatic organisms cultivated in brackish or marine environments.

Integrated Coastal Zone Management (ICZM) A process for the management of the coast using an integrated approach, regarding all aspects of the coastal zone, including geographical and political boundaries, in an attempt to achieve sustainability. The EU Commission [3] defines ICZM as a dynamic, multidisciplinary, and iterative process to promote sustainable management of coastal zones. It covers the full cycle of information collection, planning (in its broadest sense), decision making, management, and monitoring of implementation. ICZM uses the informed participation and cooperation of all stakeholders to assess the societal goals in a given coastal area, and to take actions towards meeting these objectives. ICZM seeks, over the long term, to balance environmental, economic, social, cultural, and recreational objectives, all within the limits set by the natural dynamics.

Mariculture See "aquaculture".

Offshore aquaculture A culture operation in a frequently hostile open ocean environment exposed to all kinds of sea states as well as being placed far off the coast.

Offshore co-management A dynamic partnership using the capacities and interests of different stakeholder groups for managing cross-sectoral activities in cooperation with governmental authorities in the open sea.

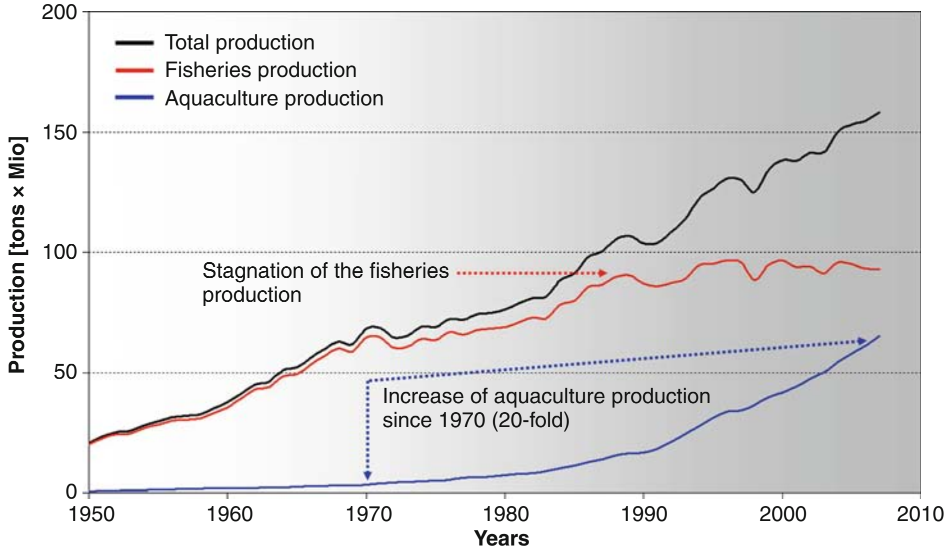
Offshore wind farms A group of wind turbines in the same confined area used for production of electric power in the open ocean. Moving off the coast to the offshore, wind turbines are less obtrusive than turbines on land, as their apparent size and noise is mitigated by distance. Since water has less surface roughness than land (especially in deeper waters), the average wind speed is usually considerably higher over the open water. Therefore, the capacity factors are considerably higher than for onshore and nearshore locations [4].

Open ocean aquaculture See "Offshore aquaculture".

Definition of the Subject

"Fisheries have rarely been sustainable." This statement by Pauly et al. [5] was based on the recognition that this lack of sustainability was induced by a serial depletion of wild stocks worldwide. Causative for this trend is due to the improved fishing technology, geographical expansion, and exploitation of previously spurned species lower in the food web. In exchange, aquaculture was often either regarded to bridge the gap between supply and demand or, in contrast, even to exacerbate this scenario.

Since the 1970s, aquaculture production has grown quite rapidly and is by now one of the fastest growing aquatic food production sectors in the world [6]. Besides the rapid development of this sector, the wide-ranging decline in fisheries yields has been enhanced by an increase in public demand for aquatic products. With an annual share of more than 15% of total animal protein supplies, the production of captured fisheries and aquaculture plays a significant role in the global food security [6]. In 2007, approximately 160 million tons of aquatic organisms were produced worldwide (Fig. 1). From that, the share of global aquaculture production amounts to almost 47%, totaling about 60 million tons annually of aquatic organisms [7, 10]. A wide range of aquatic species is raised in various systems, onshore as well as in the ocean. According to the FAO [6], approximately 300 different species, ranging from fish to shellfish, crustaceans and algae are produced in aquaculture systems. Most of these aquaculture enterprises are concentrated in well-protected and therefore favorable inshore water areas [11].



Aquaculture and Renewable Energy Systems, Integration of. Figure 1
Global production of aquatic organisms originating from fisheries and aquaculture within the last 55 years (Data source [7], modified after [8, 9])

Even probably though over-reporting its aquaculture production [12], the People's Republic of China has contributed approximately 70% to the world's aquaculture production in 2004. It is nevertheless debatable, whether this production can compensate for the global deficiency in aquatic food. In addition, the intensive traditional aquaculture of carnivorous species does not automatically relieve pressure on ocean fisheries [13]. Salmon farming, e.g., requires large inputs of wild fish as fish oil and fish meal for the production of fish feed for aquaculture. Hence, the farming of non-carnivorous species that is not dependent on fishmeal-based feeds is considered a sustainable way of producing food. However, the global increase in production originates from herbivorous species. Further, the balance between carnivorous and non-carnivorous species in aquaculture production is heavily skewed towards herbivorous species [14].

On top of this issue, an increasing limitation of favorable coastal sites for the development of modern aquaculture is evident in various countries, such as Germany, the Netherlands, Belgium, as well as others [15]. This spatial limitation is mainly caused by the lack of protected nearshore areas and by the fact that regulatory frameworks that assign specific areas for aquaculture operations are diverse and still emerging.

Further, the utilizations of coastal marine waters are manifold and quite competitive, such as shipping (trade or private), recreational activities, extraction or disposal of gravel, marine missions, fisheries, mariculture, offshore wind farms, cable and pipelines, establishment of nature reserves, and other marine and coastal protected areas. In addition, overlapping use of coastal habitats adds to the increasing pollution of coastal waters in various situations and gives rise to spatial conflicts, thus leaving little room for the expansion of modern coastal aquaculture systems.

This situation in most industrialized countries is often in contrast to the production progress in developing countries. Here, the installation of aquaculture systems benefits from the often weak enforcement of integrated coastal management schemes, which regulate equal access to the coastal resources [16, 17]. Thus, the rise of aquaculture production has specifically taken place in developing countries, especially in Asia, which holds approximately 91.4% of the global production share [10, 18, 19]. In contrast, the number of competing users within offshore regions is relatively low, thus favoring the offshore environment for further commercial development, such as offshore wind farming and open ocean aquaculture. So far, spatial regulations offshore are scarce and clean water can be expected [20]. Thus, there is an enormous economic potential for *extensive marine aquaculture* in offshore areas.

Introduction

Aquaculture has been increasing dramatically in most parts of the world and now accounts for more than 47% of the total global seafood supply [7]. Many people generally assess aquaculture positively as a potential alternative to global fishery resources, which are globally under stress as a result of overfishing. However, it also raises concerns over pollution, disease transmission, and other socio-economic impacts. Almost all efforts to develop marine aquaculture have focused on state jurisdictional waters of the coastal sea, which are generally situated within 3 nautical miles off the shore [21, 22]. With the convergence of environmental and aesthetic concerns, aquaculture, which is already competing for space with other more established and accepted uses, is having an increasingly difficult time expanding in nearshore waters [23]. Therefore, alternative approaches are needed in order to allow the expansion of the marine aquaculture sector to make a meaningful and sustainable contribution to the world's seafood supply.

The political recognition – on a national as well as on EU level – that the implementation of integrated coastal zone management (ICZM) is still fragmentary, acted as incentive to investigate in more detail how this could be overcome [e.g., 24]. This lack was recognized and led to the operation of a EU-Demonstration Programme on Integrated Coastal Zone Management from 1996 to 1999. This Programme was designed around a series of 35 demonstration projects and six thematic studies. In 2002, based on the experiences and outputs of the Demonstration Programme, the EU-Commission adopted a recommendation concerning the implementation of Integrated Coastal Zone Management in Europe (Recommendation of the European Parliament and of the Council, 2002/413/EC). In Germany, this generated a call of the Federal Ministry of Education and Research to the various federal states to develop projects that address ICZM on a regional level. In 2004, the program *Coastal Futures* [25], which tied up various administrative and scientific bodies and the public along the west coast of the State of Schleswig-Holstein, was granted funding. This program focused primarily on two issues: [1] to develop the future of the coast as a living, working, and recreational space for the local population, and [2] to consider the potential contribution of coastal resources to the sustainable development on the national and EU/global level, i.e., by providing regenerative energy by wind power. In order to sustain sufficient open space for future development, the idea of combining offshore wind power generation with other uses, such as aquaculture operations, emerged [26]. Marine aquaculture is a growing enterprise in Germany as well as in the whole of Europe, strongly motivated by the decline of fisheries production and the search for alternative income options for rural peripheral coastal regions.

In order to stimulate multifunctional use of marine space, it was decided to develop a project on a showcase basis, which deals not only with different scientific fields but also with private–public partnerships and the relevant institutional bodies. In the following, an overview on the current state of research undertaken within this focus is provided. Offshore wind farms will hereby act as a case example for renewable energy systems in the open ocean.

Offshore Aquaculture – A New Addition to Marine Resource Use

Farming in the open ocean has been identified as one potential option for increasing seafood production and has been a focus of international attention for more than a decade. *Offshore aquaculture* or *open ocean aquaculture* are operations in a marine environment fully exposed to all kinds of oceanographic conditions [27] as well as located at least 8 nautical miles off the coast [15] to avoid the many stakeholder conflicts in nearer coastal areas [28]. The procedures and applied techniques for the cultivation of organisms mainly depend on the species; their life cycle determines the phases of cultivation and the location for the grow-out, where market size will be reached. First trials of cultivation were based on *extensive marine aquaculture*, which – in contrast to intensive aquaculture – is a line of production with little impact on the marine environment. These aquaculture operations are characterized by (1) a low degree of control (i.e., environmental control, nutrition, predators, competitors, and disease agents), (2) low initial costs, (3) low level technology, (4) low-production efficiency, and (5) high dependence on local climate and water quality (natural water bodies, such as bays, ponds, embayments) [29]. Mostly, they are regarded as a sustainable line of production.

Moving to the open ocean has been considered as a means for moving away from negative environmental impacts and negative public perception issues in the coastal zone. Favorable features for the transfer to open ocean waters include ample space for expansion and thus reduced conflicts with other user groups, lower exposure to human sources of pollution, the potential to reduce some of the negative environmental impacts of coastal fish farming, and optimal environmental conditions for various marine species through the larger carrying and assimilative capacities. However, this move should not be seen as an "out of sight, out of mind" attitude, as open ocean development will also come under scrutiny by the institutional bodies as well as by a more and more educated public. It is expected that, because of economies of scale, the open ocean farms of tomorrow will be larger than the present nearshore farms. Therefore, higher levels of waste can be generated. Even if greater residual effects occur, deeper waters and lower nutrient baselines are expected to reduce impacts from open ocean operations through wider dispersion plumes of nutrients, as compared to similarly sized nearshore operations. However, there will be a point when open ocean ecosystems will eventually reach their assimilative carrying capacities [30].

Offshore Wind Farms as a Case Example for Renewable Energy Systems

Wind energy continues to be the world's most dynamically growing energy source [31]. Drawing on the example of Germany, the first initiative toward an economy based on renewable energy resources was set by the governmental decision in the year 2000 to gradually reduce the use of nuclear energy and to respond to the gradually diminishing fossil- and nuclear-energy reserves. Simultaneously, the output of CO_2 to the atmosphere would be reduced in accordance with the Kyoto protocol as well as the dependence on conventional fossil-energy resources is lowered.

As high and reasonably steady wind speeds are characteristic in Northern offshore areas, these areas are prime candidates for renewable energy production by wind-energy farms. For instance in the North Sea, a major political incentive exists currently to install large offshore wind farms [32, 33]. Thus, the emerging branch of offshore wind farms appears as a new stakeholder on the list of users [34, 35].

So far, this development has been successful to such an extent that around 7.2% of the total energy consumption in Germany is covered by this technology. At the end of 2007, Germany had an installed capacity of 22,247 MW, generated by 19,460 mainly land-based operating wind turbines [36]. Within Europe, as the leading market for wind energy with over 57 GW, Germany thus accounted for 39% in terms of the total installed capacity and still remains the world's leader. However, with the North American market currently experiencing a strong growth, it is expected that the US market will soon overtake Germany [37].

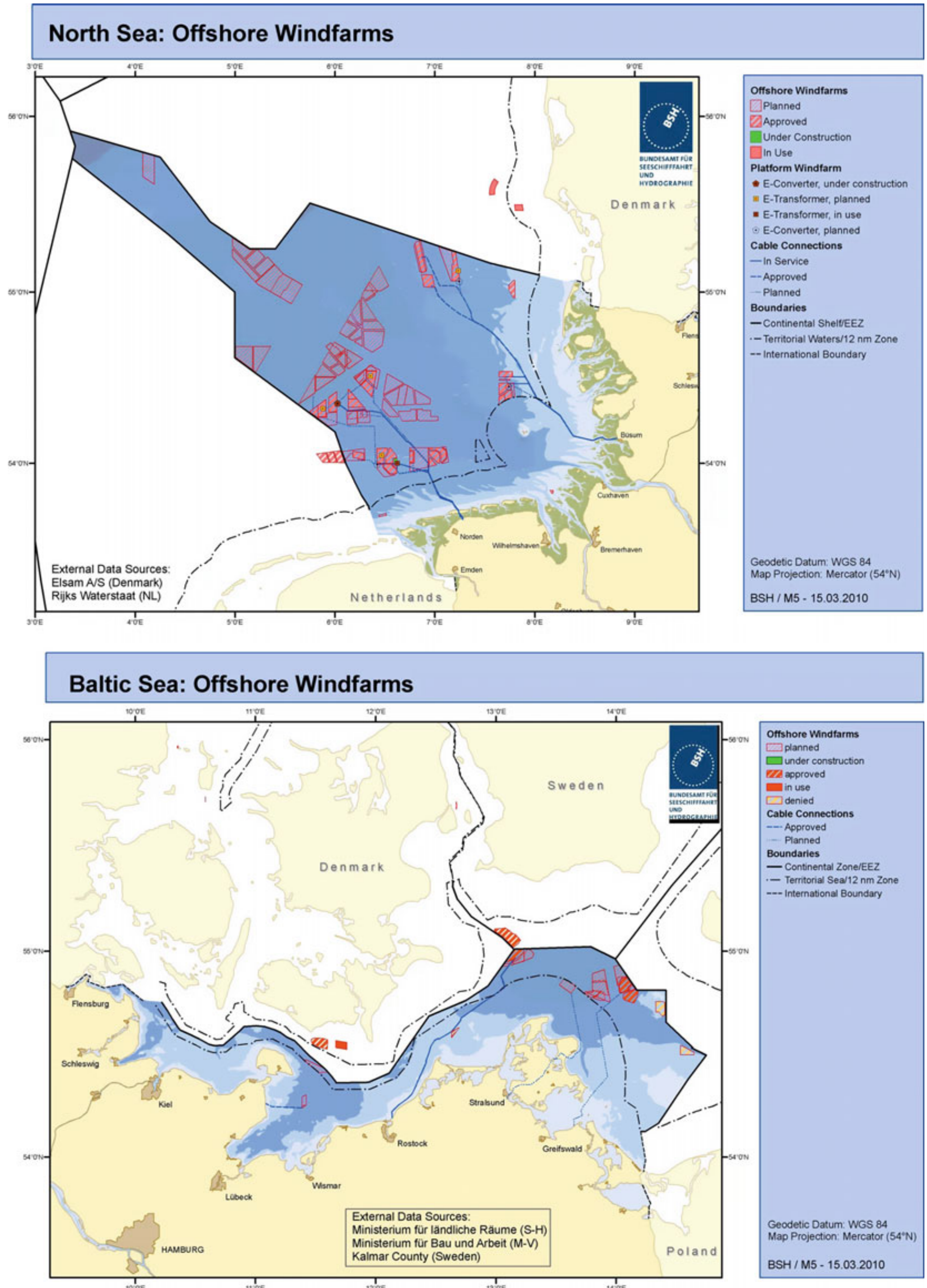
At present, 60 project applications for wind farms in the Exclusive Economic Zone (EEZ) of the German North Sea and in the Baltic Sea are in the planning process stage with the total number of wind turbines per farm ranging between 80 and 500 [26] (Fig. 2). In November 2001, the Federal Maritime and Hydrographic Agency (BSH) granted the first approval for the installation of a pilot offshore wind farm. Since then, a total of 23 wind farm development projects have been approved in German waters, most of them planned seaward of the 12 nautical miles zone [38]. Currently, a larger test farm of about 12 wind turbines (5 MW class) at the "Borkum West" site are in operation (Fig. 3) [39]. Experience gained in this project should give developers practical knowledge in the construction and operation of offshore wind farms at depths (down to 50 m) and at distances from the shore (up to 50 nautical miles and more) that are beyond comparison to those anywhere in the world [31, 33].

In contrast to neighboring European states, the prospect of moving wind energy developments offshore stagnated in Germany for years mainly due to a very complex licensing procedure and the high environmental constraints [33, 40]. A further obstacle roots in the spatial competition of offshore wind farms with other utilization of the marine waters in the German Bight [41, 42]. However, despite the number of competing users within offshore regions being lower compared to coastal areas [43], the quest for spatial efficiency remains to be a key incentive also for offshore developments in the future.

Moving Offshore: The Multiple-Use Concept

The plans for the massive expansion of wind farms in offshore areas of the North Sea triggered the idea of a combination of wind turbines with installations for extensive shellfish and macroalgae aquaculture [15, 26]. Offshore wind farms provide an appropriately sized area free of shipping traffic as most offshore wind farms are designed as restricted-access areas due to hazard mitigation concerns. Concurrently, the infrastructure for regular service support is readily available, and hence such sites provide an ideal opportunity for devising and implementing a multiple-use concept [42, 44]. However, in contrast to coastal inshore areas where beaches and their adjacent nearshore zones act as buffers to absorb wave energy, offshore regions are high-energy environments, fully exposed to waves, weather, and currents. Numerous studies have demonstrated that waves can reach remarkable heights (up to 10 m) in the offshore areas of the North Sea [e.g., 45, 46]. In this context, the solid foundation structure of wind turbines provides support for anchoring cultivation devices that can withstand the harsh oceanic conditions [47]. Furthermore, offshore structures are well known for their artificial reef function, thus supporting biodiversity in the ecosystem. The offshore water quality, which is a major issue in all kinds of aquaculture operations, is regarded to be excellent in comparison to inshore areas [48, 49]. Finally, the multifunctional use of offshore areas reduces conflicts between stakeholders if activities are concentrated and conjointly managed within so-called multiple-use marine areas. This, in turn, increases the amount of open ocean territory free of utilization by man. All of the above issues are considered as key incentives to move offshore with aquaculture operations.

In view of the many interests for the offshore move, different suggestions for technical structures for open



Aquaculture and Renewable Energy Systems, Integration of. Figure 2
Maps indicating all application sites for wind farm projects in Germany. At the top, the North Sea, below the Baltic Sea areas (Modified after [38])

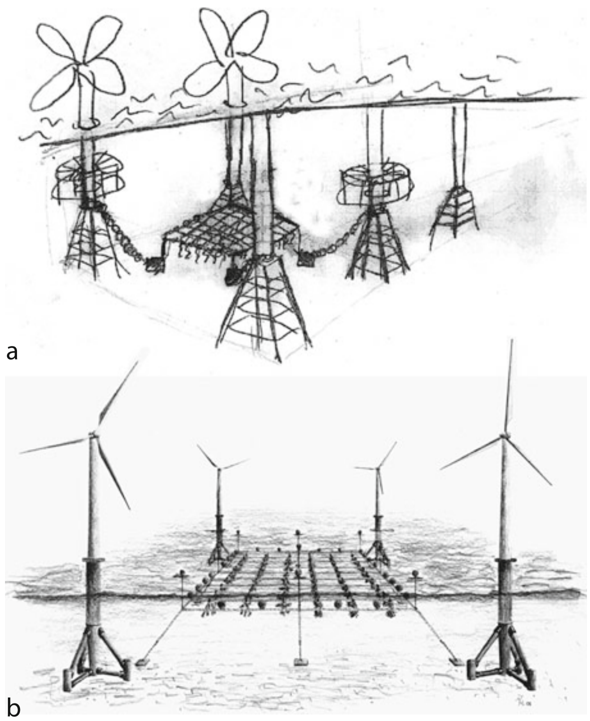
Aquaculture and Renewable Energy Systems, Integration of. Figure 3
Offshore wind farm Alpha Ventus. (**a**) Shows the transfer of the windmill tripods to the harbor of Wilhelmshaven and (**b**) displays the setup of an offshore windmill (REpower MI 068 [39])

ocean aquaculture were proposed (see proceedings of various OOA-Conferences [e.g. 50, 51]), which could cope with the harsh environmental conditions that place an enormous stress on the employed materials. It would be advantageous for the global offshore aquaculture development to plan for a combination of uses. While windmills use the wind above the surface to produce energy, their fixed pylons, commonly concrete fundaments (gravity foundation), metal jackets, tripods, or triples offer a possibility to connect systems used in aquaculture (Fig. 4). The combination of the respective two industries has to cope with the forces generated by the high-energy environment.

Since 2000, when the co-use of wind farms for off-bottom offshore cultivation [26] in the German Bight was proposed, several studies have been conducted to elucidate the potential as well as constraints of this offshore alternative for extensive aquaculture. Two pioneer studies, the project *Roter Sand* and *Offshore Aquaculture* were conducted between 2002 and 2004 by the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany. These two projects followed a complex approach to obtain data about suitable indigenous candidates for the offshore cultivation [15], the technical requirements of longline systems for the cultivation of mussels or oysters [8, 9] and algal cultivation systems [53]. Insights into the feasibility of offshore seed and mussel production concerning larval, nutrient, and phytoplankton concentrations [8, 9, 54] were provided, and the existing legislation and regulations concerning marine aquaculture in Germany were listed [21]. In addition, all stakeholders potentially involved in a multifunctional use of offshore wind farms for aquaculture were identified [42]. This successful multifaceted approach helped to disperse many concerns and doubts on the offshore idea and initiated a sequence of and relations between various following projects, which are displayed in Fig. 5.

Candidates and Techniques for the Multi-Use Concept

In general, the cultivation process should consider only indigenous species for marine aquaculture operations to



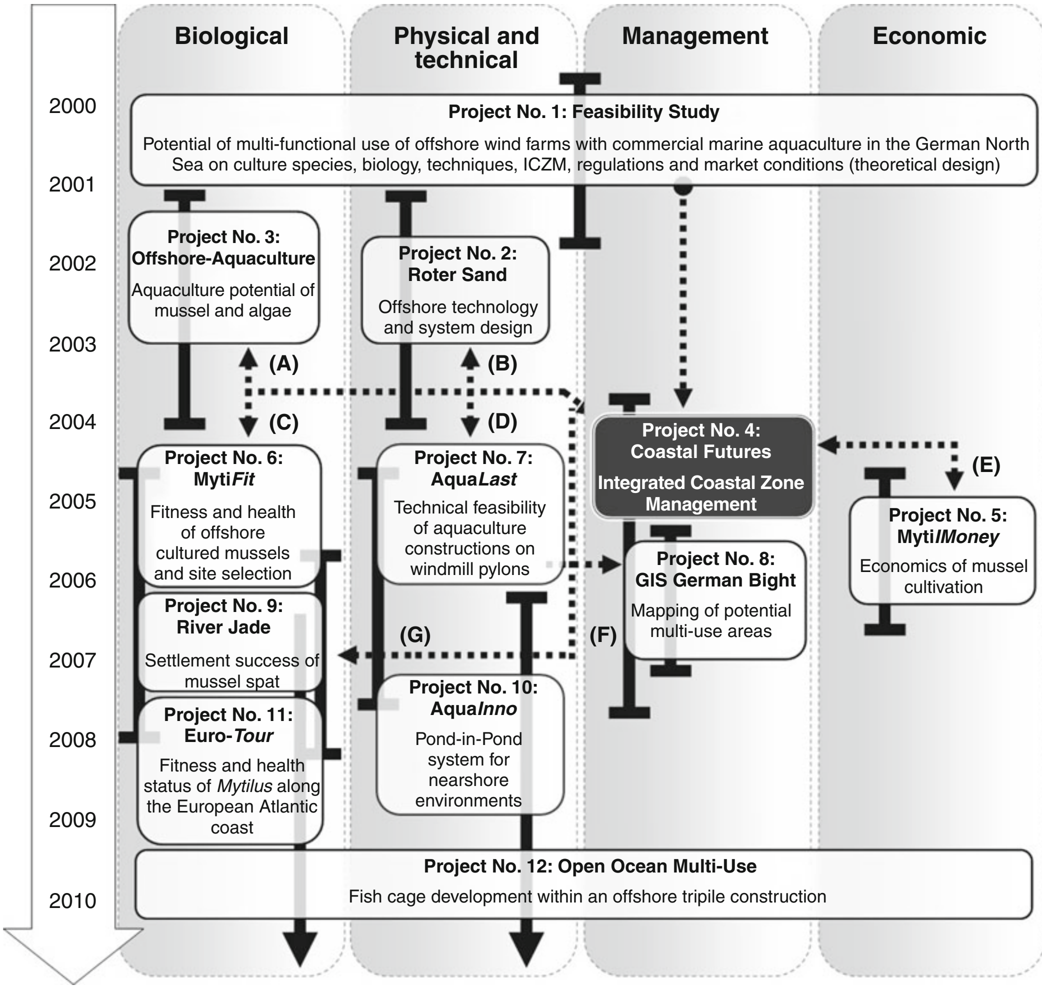
Aquaculture and Renewable Energy Systems, Integration of. Figure 4
Potential multifunctional use of fixed underwater structures of wind turbines for the operation of aquaculture facilities: 12 years ago and today (2010). (**a**) First drawing ever for the multi-use concept, including alternative solutions of oyster cages and mussel collectors attached to longlines in the inner section of the wind farm or offshore-rings (collar systems) attached directly to the pylon. The latter system can be submersed in case of wind-turbine maintenance. (**b**) Presents a design of a single mussel plot within a group of four wind turbines (not to scale) (Modified after [52], Buck personal drawing)

avoid the disruption with the local marine flora and fauna. This limits the economic opportunities of marine aquaculture enterprises since in certain sites only a few indigenous candidates are regarded as high-value species. Following a feasibility study by Buck [26], in Germany only culture species with modest service needs can be considered as favorable candidates for offshore aquaculture. In the offshore test trials in Germany, most suitable candidates suggested and tested were the sugar kelp (*Laminaria saccharina*), oarweed (*L. digitata*), dulse (*Palmaria palmata*), the blue mussel (*Mytilus edulis*), and two oyster species, the Pacific oyster (*Crassostrea gigas*) and the European flat oyster (*Ostrea edulis*). Mussels and seaweeds, for example, are cultured mainly in extensive systems throughout the world [8, 56, 57]; the latter occurs for historical and traditional reasons mostly in Asian countries.

According to Tseng [58], the cultivation procedure of brown seaweeds can be divided into two separate steps: In step (1), the seedling phase, spores are artificially released from mature sporophytes and seeded on a given substrate (ropes wrapped around plastic frames), where germination of gametophytes, the sexual maturation of male and female gametophytes, and finally, the development of zygotes into juvenile sporophytes takes place. In step (2), the grow-out phase, culture ropes with juvenile sporophytes are transferred to the open sea. In the grow-out phase, the macroalgal sporophytes grow on ropes for one season to a frond length of approximately 2 m.

When natural reproduction of mussels occurs, gametes are released into the water column where fertilization takes place [59]. The larvae undergo all trochophore and veliger stages when settling on a given substrate to start metamorphosis. According to Pulfrich [60] and Walter and Liebezeit [61], this process normally takes place at spring time (larval peak in May) in the German Bight. The cultivation of blue mussels can be divided into two steps: in step (1) the naturally occurring spat collection is achieved by deploying artificial substrates [62]. Usually, spat collectors are made out of unraveled polypropylene lines or sisal ropes, to offer the mussel's post larvae substrate for settlement [56]. After several months (step 2), collectors are retrieved and mussels thinned out and reseeded on ropes to provide space to improve growth and allow fattening [63, 64].

To operate culture phase (2) of both species, macroalgae and bivalves, an appropriate system design, such as suspended longlines or floating ring-structures, have to be deployed and securely moored in order to resist the stress forces of incoming waves and tidal currents, as well as swell. In addition, it was necessary to assess what kind of technical structure supports best the growth of the organisms (e.g., prevention from loss or mortality) while also assessing whether such systems provide reasonable production returns. Finally, potential combinations with offshore wind turbines had to be assessed.



Aquaculture and Renewable Energy Systems, Integration of. Figure 5
Chronological order of conducted and ongoing research projects dealing with the combination of offshore wind farming and open ocean aquaculture. Project No. 1, the feasibility study, constituted the basis for all subsequent research. The *Coastal Futures Project* acts as a key node project to which the other projects either have contributed or by which they have been stimulated because of its transdisciplinary approach. It is visible that: (**a**) calls the wind farm developers' attention to offshore aquaculture; (**b**) and (**c**) include authorities and fishermen into the planning process for site-selection criteria of appropriate aquaculture sites; (**d**) involves offshore engineers and wind farm developers/operators into the technical part of an offshore aquaculture enterprise; (**e**) introduces (mussel) fishermen to the co-management idea and appraises the economics of mussel cultivation; (**f**) supplies authorities with maps and tools to limit regional stakeholder conflicts, (**g**) establishing an inshore reference station to support the data collected offshore, and (**h**) testing the first fish cage mounted within a tripile construction (Modified after [55])

However, currently even candidates requiring a semi-intensive as well as intensive cultivation process are in the testing phase. Salmon (*Salmo salar*), seabass (*Dicentrarchus labrax*), seabream (*Sparus aurata*), or some flatfish species are discussed for aquaculture in fish cages below windmill platforms at different offshore sites worldwide. Fish will firstly be reared in land-based facilities and will then be transferred as fingerlings to the offshore site and released into the submergible fish cages. After reaching market size, the fish will be harvested and removed to the land and will undergo normal processing procedures.

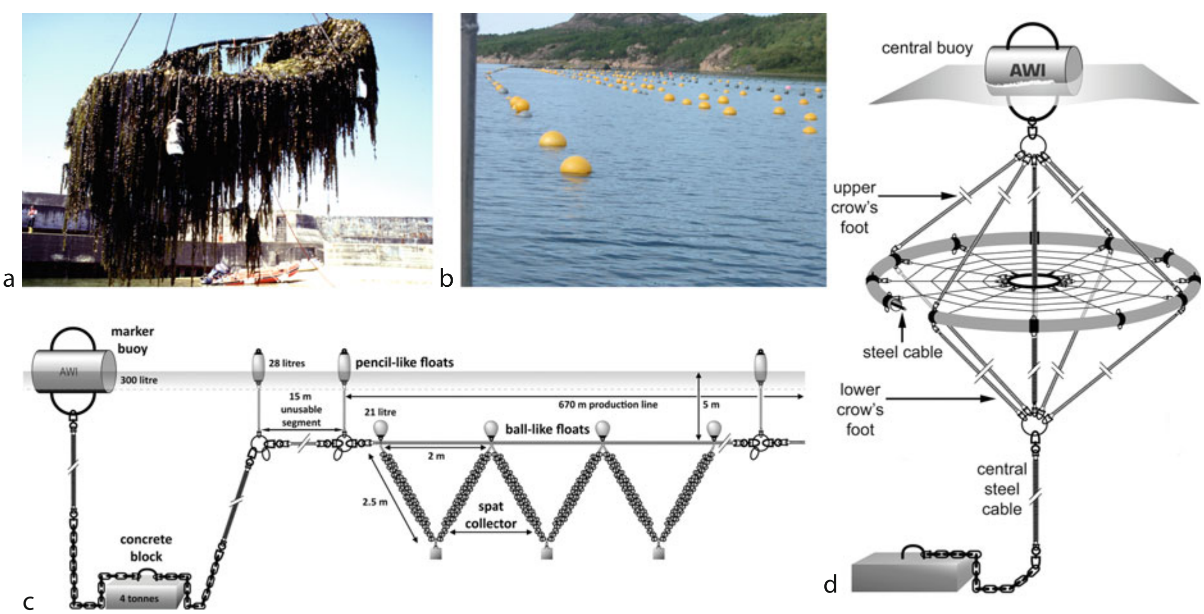
Relocating cultivation systems offshore into high-energy environments requires the development of suitable culture techniques able to withstand the harsh conditions and minimize risk of economic loss [65].

Several techniques exist to cultivate mussels and seaweed either in co-culture or in single culture. Basically, both organisms are cultured in a suspended manner in the water column, floating or submerged. The use of rafts, longlines, and ring methods dominate. The latter two were the main cultivation techniques used in test trials offshore wind farm areas [8, 53, 56] (Fig. 6).

Major difficulties in the development of suitable techniques for open ocean aquaculture are – as mentioned above – the harsh environmental conditions which place an enormous stress on materials. Depending on the acting hydrodynamic forces, different technical setups can be distinguished. One of the interesting possible linkages of aquaculture is the combination with offshore wind farms as these would provide stable fixing structures for the cultivation systems. This is especially relevant from an economic point of view as so far the costly infrastructure for offshore aquaculture systems is one of the major drawbacks in the development.

Status Quo of Offshore Aquaculture Research Activities in Wind Farms

Only a few scientific studies dealing with the prospects of offshore aquaculture were available before 2000, and little was known about the biotechnological requirements, economic potential, or the socio-economic influence on the general feasibility of offshore aquaculture. Very few long-term experiments under harsh hydrodynamic conditions exist, e.g., Langan and Horton for offshore mussel cultivation [66]; Neushul and Harger [67]; Neushul et al. [68] for offshore seaweed cultivation. However, data on system and species performance are urgently needed to derive methodologies for the assessment of its environmental and economic viability. Therefore,



Aquaculture and Renewable Energy Systems, Integration of. Figure 6
Aquaculture constructions suitable for the cultivation in high-energy environments. (**a**) Offshore ring design for the cultivation of macroalgae (here: harvesting after grow-out in the harbor of Helgoland), (**b**) example of a nearshore, submerged longline design for mussels and oysters, (**c**) schematic drawing of a submerged longline suitable for exposed sites, and (**d**) a technical illustration of the ring design and its mooring system (Modified after [8, 9, 53])

the assessment of the potentials and constraints for sustainable aquaculture development in all marine habitats requires input from various scientific disciplines in order to direct this development towards a successful aquaculture undertaking. In particular, this holds true for offshore aquaculture, where little practical experience is available to date, although research in this area is evolving rapidly (e.g., Buck [15], Turner [69]; Pérez et al. [70]; Bridger and Costa-Pearce [51]; Dalton [71]; Naylor and Burke [72]).

The offshore wind farm and aquaculture investigations initiated an integrated assessment of theoretical and practical challenges of aquaculture operations in the North Sea. Several studies were carried out, all of which contributed to specific aspects of such a combined utilization of offshore space. These were:

(a) *Biological studies*, in which the focus was placed on cultivation and subsequent performance characteristics of indigenous bivalve, seaweed, and fish species exposed to extensive offshore aquaculture farming conditions. Further, the health status and infestation rates with parasites, bacteria, and viruses of candidates were determined to gain reliable predictions on where the highest growth rates and best product quality for consumers can be achieved. In nearshore intertidal areas, mussels and oysters are particularly exposed to high concentrations of pollutants, pesticides, near surface agents, estuarine run-offs, etc. that can pose a threat to consumer health. Buck [8, 9, 15] reported high growth rates for mussels cultivated in the German Bight. The scope of growth, i.e., the energy available for growth, is usually directly and positively correlated to a good overall health condition of the respective organism [73]. But organisms with high growth rates and a healthy appearance are no guarantee of a healthy food for human consumers. For instance, in coastal waters, eutrophicated by urban sewage, mussels show good growth performance. The microbial status of these mussels, however, mostly excludes them from consumption since they might carry various human pathogens. Even in developed countries with strict legislation for the treatment of wastewater, mussels can function as carriers of vector diseases. Whether this is also true for offshore cultivated mussels, where the environment is cleaner due to dilution of contaminants, remains open. Data for offshore-produced mussels, generated according to the analysis protocols of controlling authorities, are not readily available for all cultivation sites. However, new regulations are in the implementation process in all of the EU states and will fulfill the prerequisites for an official sampling design and assessment (i.e., sanitary survey).

To evaluate the significance and comparability of the employed parameters in a broader geographical context, the area of investigation was extended along the Atlantic coast from southern Portugal to northern Denmark. Further on, the closely related Mediterranean mussel *Mytilus galloprovincialis* was included in the analysis to test the effectiveness of all the parameters in different species.

Investigations on fish species for submerged cage-systems included aspects on growth, welfare, stress in exposed environments, and health.

(b) *Physical and technical studies* investigated the effects of the prevailing hydrodynamics on candidates and culture constructions at specific offshore sites. At the same time, the necessary technical requirements for farming structures in high-energy environments and their possible combination with offshore wind farms were assessed. New system designs for offshore farming were developed and prototypes (e.g., offshore ring, offshore collector) were tested. Technical details about the microstructure of artificial substrates were addressed to increase production per meter longline under offshore conditions. In addition to offshore seaweed and mussel cultivation, new technologies for submerged fish cages were investigated.

(c) *Management and institutional studies* focussed on the analysis of potential management approaches to implement a multi-use concept of offshore areas. Hereby, the various stakeholders and their respective views and knowledge systems were integrated. Against the background of the social and institutional dimensions, particular emphasis was given to the interrelationship between scientific findings on the one hand and effective implementation on the other. Key aspects included the social acceptance of combined use, as well as the possible management strategies that would govern it. This endorsed the examination of the prevailing case laws and regulative and management framework conditions, as well as a suggestion of decisive offshore co-management strategies to support such activities. In this process, the continuous inclusion of the stakeholders in a participatory manner was a prerequisite. To address the respective technical, economic, social, and political challenges of mariculture and offshore wind farms, specific co-management strategies were elaborated that are either more results-oriented (e.g., for integrating technical knowledge of the two sectors) or more process-oriented (e.g., for establishing new linkages between different groups). Thus, in cooperation with governmental authorities, co-management in the offshore makes use of the capacities and interests of the respective stakeholder groups and employs these in managing cross-sectoral activities.

(d) *Economic studies* conducted an economic evaluation of such multi-use concepts in offshore locations that take into consideration market conditions as well as investment and operating costs.

All the above listed conceptual approaches relied on results of a theoretical feasibility study (Fig. 5) [26], which was carried out prior to practical research in the field. All of the results contribute to the *Coastal Futures* Program and support the quest to find innovative new approaches for sustainable use and alternative livelihoods of coastal populations.

Overview of Biological and Technical Investigations

Over the last decades, substantial insights have been gained on the terms and conditions active in the offshore environment. However, these data are only partly useful for the selection of offshore aquaculture sites because they have been gathered primarily for other user needs and thus lack the essential specificity to address the biological and cultivable potential of these sites. Prior to a multifunctional development comprising mariculture activities, it is therefore necessary to determine the appropriate biological, technological, and management requirements, as well as the performance characteristics that would allow the employment of favorable and cost-effective methodologies. To meet this end, special focus was placed on the combination of extensive offshore shellfish, seaweed, and fish farming at exposed sites within the proposed offshore wind farm boundaries.

Due to the wide spectrum of open questions, the outcomes are quite manifold. In the following, first results according to their contributions towards the main research topics involved are presented.

Biological Studies The theoretical *Feasibility Study* [13, 24] was aimed to ascertain the biological, technical, and economic feasibility of an offshore marine aquaculture structure with respect to the cultivation of marine organisms within wind farm sites in the German North Sea. One result was that to date, in terms of commercial marine aquaculture, Germany had little knowledge and background in offshore aquaculture compared to many other coastal countries throughout the world. Nevertheless, a synthesis of a selection of parameters (e.g., geophysical and biological parameters) allowed the identification of suitable candidates for commercial offshore aquaculture. These candidates include blue mussels (*Mytilus edulis*) and oysters (*Ostrea edulis*, *Crassostrea gigas*), which could be maintained extensively in the offshore region. Moreover, labor requirement for these candidates as well as for seaweeds, such as the sugar kelp (*Laminaria saccharina*) and dulse (*Palmaria palmata*), is supposed to be low.

Further, the biological feasibility of cultivating mussels, oysters, and kelp within offshore wind farm sites was assessed. The growth of these species is excellent in the rather eutrophicated offshore environments of the North Sea, but can differ depending on exposure sites, system designs, installation modes, and season.

For instance, settlement of young mussels on artificial collector substrates decreases with increasing distance from the shore [74]. However, this does not limit the economic potential if the thinning procedure will be omitted, following a "One-Step-Cultivation" concept [15]. In general it was found that mussels are free of parasites at offshore locations due to dilution effects and the interrupted reproduction cycles of some macroparasites [75]. Special focus was placed on the overall health status of mussels cultured under different conditions, and the impact on economic aspects was investigated [76]. Specific aims of the projects were the development of suitable offshore spat collecting techniques, detailed knowledge about parasites (macro and micro), bacteria and virus infestations at different sites, implementation of biodiagnostic techniques for the health analysis of cultured mussels, and collection of all relevant data (e.g., shell stability and attachment strength of mussels), for the further processing of mussels as a product for human consumption.

Hydrodynamic forces support length increase of seaweed blades when transferring young sporophytes to sea. These algae will adapt to the occurring loads and develop strong holdfasts, preventing detachment of the entire plant [77].

Modified and improved techniques for offshore farming withstand high-energy environments, but will certainly cause higher investment costs. Therefore, site-selecting criteria for a culture area should be clearly identified to assess economic risks. Important for the cultivation success is the water quality. The analysis of the cultured organisms with biodiagnostic tools provides detailed insights into the water conditions the animals live in. By this approach, reliable predictions are possible as to which locations grant highest growth rates and best product quality for consumers. Preliminary results attest offshore areas satisfying settlement success and excellent growth rates [78], and low infestations with macroparasites [79], microparasites, bacteria, and toxins [76]. The results on consumption suitability show that water quality regarding the concentrations of pollutants in offshore areas of the German Bight is quite good. Lysosomal membrane stability is mostly relatively low at all tested nearshore and offshore sites. Interestingly, growth rates of the hanging cultivated mussels are not affected by this low fitness parameter [58].

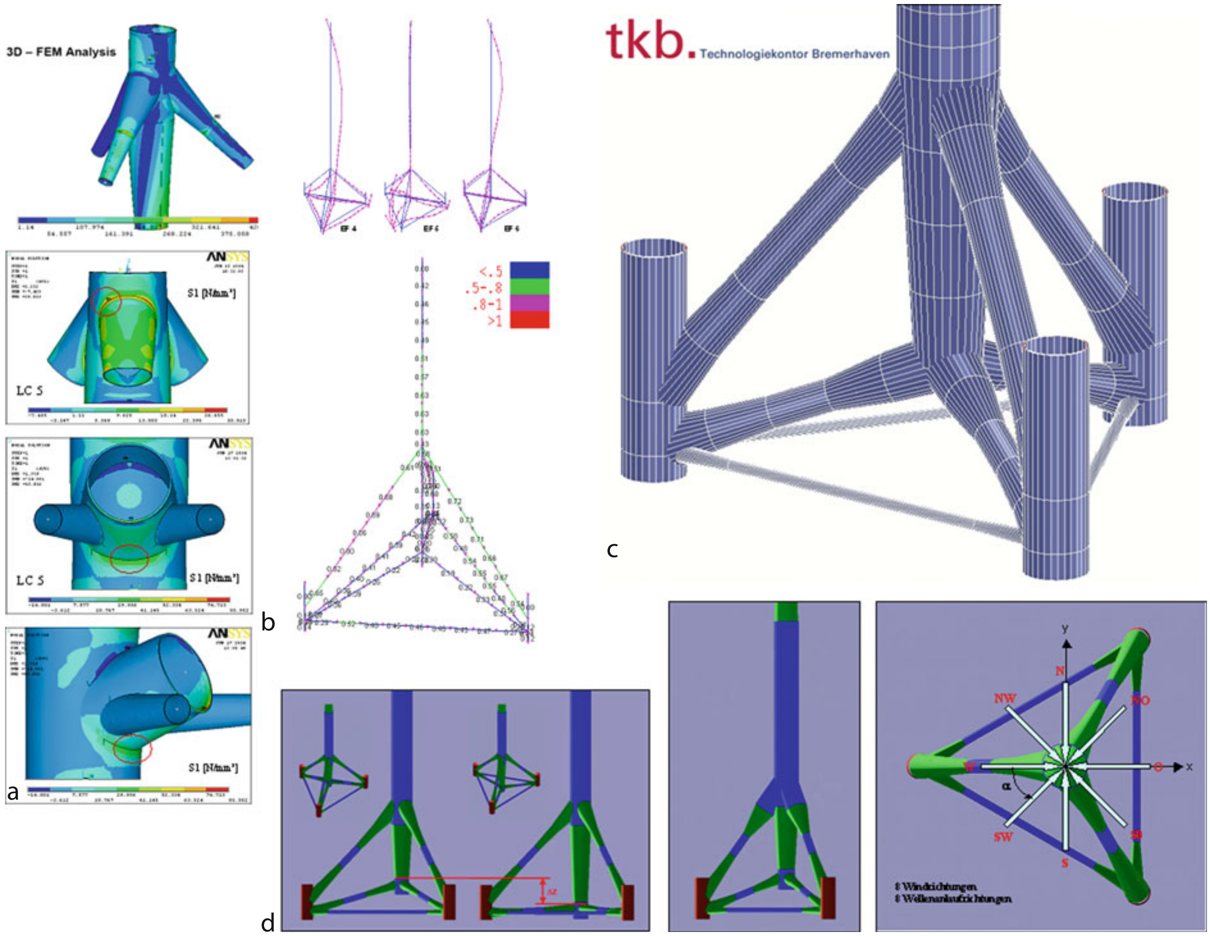
First results on investigations along the Atlantic Coast show that mussels originating from offshore habitats have a better health status regarding the infestation with macroparasites and microparasites (Buck and Brenner, unpublished data). While macroparasites are still infesting mussels in nearshore areas in the Wadden Sea (the Netherlands, Germany, Denmark), microparasites are absent.

Physical and Technical Studies The results above allowed the identification of two offshore aquaculture systems that were best suited for offshore operations from a biological point of view. Depending on the acting hydrodynamic properties, different technical setups are regarded as favorable. The first one is a floating and submergible ring system for the cultivation of seaweed. It withstands rough weather conditions and allows easy handling [53]. The second system is a submerged longline design for blue-mussel culture [8]. The longline should ideally be installed 5 m below the water surface and should be connected to foundations of offshore windmills (Fig. 7) [47]. For the longline, polypropylene proved to be an appropriate material. The system design is made of various connected segments allowing an easy harvest and replacement of all parts of the construction. However, more technical engineering research is required to find the most cost-effective mode of construction and the best choice of materials (e.g., little corrosion, longevity in spite of mechanical stress) so that easy handling can be guaranteed under relatively harsh weather conditions (cf. construction, deployment, retrieval, service, repairs).

The experimental design also allowed work on such issues as the efficiency of the collecting devices themselves. Healthy mussels will reach market size in offshore conditions only if they are firmly attached to their artificial substrate. As mussels growing on suspended substrates need about 15 months [8, 9] on average to reach market size, they must survive one winter and withstand storm events producing wave heights up to several meters. Continuing investigations on the health and quality of market-sized mussels would be moot if mussels failed to stay attached to substrate gear.

To date, most available substrates are designed and deployed for nearshore use under calm water condition. However, it was found that improvement for construction of new collectors that are feasible for offshore cultivation is in mandate. Research showed that new substrates should have felt-like structures around the core of a collector for larval attraction and long appendices in high density to interweave the mussel conglomerates with the substrate [80]. Future investigations should focus further on the fabrication and testing of a prototype of this collector, concerning the results of this study. Besides providing optimal larval attraction and attachment for juvenile mussels even under winter conditions, any new substrate should proof its durability under conditions of a daily farming routine. This would include mechanical thinning, harvesting processes, and tests on the reusability of the material.

The technical realization and the implications of aquaculture technical requirements on design and construction of the grounding construction of offshore



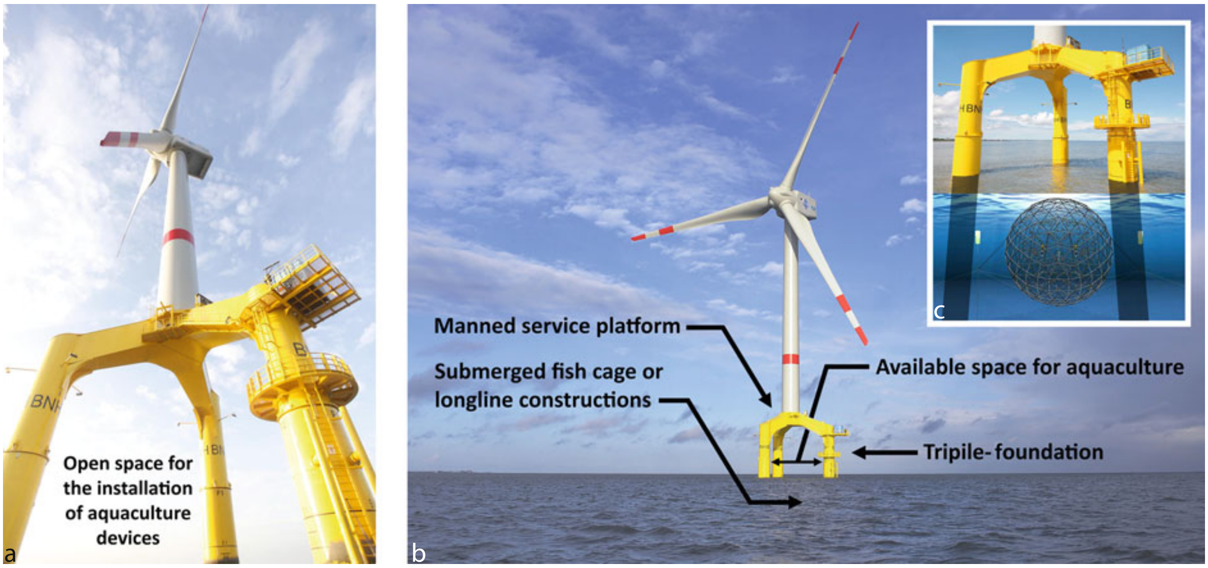
Aquaculture and Renewable Energy Systems, Integration of. Figure 7
Modeling of potential attachment points for the combination of longline connections to a tripod foundation. (**a**) Displays alternative connection points, (**b**) shows the generation of representative loads on the wind-energy installation, including vibrations, (**c**) shows the respective tripod foundation for offshore use in depths of about 20–50 m, and (**d**) shows the development of a static model (3–5 MW class) [47]

wind turbines were considered. So far, modeling and experimental validation of a submerged 50 m longline aquaculture construction mounted between two steel piles, 17 nautical miles off the coast, show significant forces of up to 90 kN (equivalent to 9 t) induced by waves of up to 1.8 m significant wave height and tidal currents of up to 1.0 m/s [81]. Given the high-energy environment in the North Sea and the non-linear relationship between water movement and its resulting forces, even higher mechanical loads are to be expected within the life cycle of such an arrangement. These must be taken into account when developing techniques for larger-scale offshore cultivation within wind farms.

Finally, a new cage design project has been initiated, where it will be investigated whether aquaculture of fish in between a tripile construction below a windmill has the potential to enlarge the diversity of candidates to be grown offshore (next to bivalve and seaweed) as well as widening the potential of offshore farming within wind farms. First insights are shown in Fig. 8 [82, 83].

Management and Institutional Considerations

From a spatial planning perspective, the ocean space in the Exclusive Economic Zones (EEZ) cannot be considered any more as "commons" in the sense of Ostrom



Aquaculture and Renewable Energy Systems, Integration of. Figure 8
Tripile construction for the secondary use for fish cages. (**a**) Shows the open space within a tripile foundation to be used for aquaculture purposes, (**b**) displays a lateral view of the Bard Windmill and the access to the fish cage, and (**c**) is a photo animation and gives an idea how a fish farm, such as an aquapod, could be moored below [82, 83]

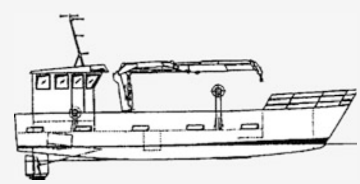
et al. [84] wherein individuals or groups have the right to freely consume and return any kind of resources. As a matter of fact, the "tragedy of the commons" situation Hardin described in 1968 [85], has already been reached for most of the oceans today. Offshore waters are in a process of transition, revealing diverse and heterogenic interests in marine resources. For instance, the development of offshore renewable-energy systems is an international priority driven by the need to reduce the dependence on fossil fuels and decrease human impacts on the global climate regime. Simultaneously, the demand for high-quality seafood is accelerating globally. This leads to an increased complexity and thus to limitations in developing and managing the different and often spatially overlapping maritime activities independently of one another. The upcoming new utilization patterns of the German North Sea, such as wind farms, but also Marine Protected Areas (MPAs) reported to the EU commission in Brussels for the "European Natura 2000 network," reveal a trend toward the development of permanent constructs. Both are examples for new forms of use with a high spatial demand [86]. Not all uses are compatible with each other and user conflicts with existing activities, such as fisheries, maritime traffic, or military missions are preordained. The planned large-scale offshore wind farms as well as designated MPAs are prime examples for the development of lasting marine structures that take up a surface area of several square kilometers each [55].

At the same time, the increasing demand for high-quality foods worldwide accelerates the development of marine aquaculture. This potential newcomer can be expected to become an additional competitor in offshore waters [87], contributing to the increase in spatial competition and complexity in the ocean [20]. Conflicts among the respective user groups are inevitable. The growing competition for space represents a major challenge for further developing or even maintaining all forms of marine aquaculture, as well as freshwater fish farming. However, area choice is crucial and spatial planning has a key role to play in providing guidance and reliable data for the location of an economic activity, giving certainty to investors, avoiding conflicts, and finding synergies between activities and environments with the ultimate aim of sustainable development [88]. The inclusion of all stakeholders in this process to find synergies in the open ocean is crucial.

Ongoing multidisciplinary social-science research in Europe shows that it is feasible to establish spatially efficient and effective wind farm–mariculture co-management regimes. A window-of-opportunity has opened as both groups have realized that they may benefit through the integration of operation and maintenance (O&M) activities vis á vis gaining support in collaborative action by the current impetus of the new EU Maritime Policy. The operation and maintenance of any offshore installation is a major challenge due to restricted logistics and accessibility, forming a large part of the overall costs. A five-to-ten time more expensive scale of operation and more difficult logistics for maintenance and/or harvesting compared to nearshore or onshore sites have to be taken into account [89–91]. Experiences with existing wind farms and mariculture sites off the coast show that work at the sea is not only significantly more cost-intensive, but also more time consuming than on land [92].

There are certain rights and duties involved if prospective spatial and organizational interaction of O&M activities of offshore wind turbines and mariculture installations are to be combined [20]. Different values, perspectives, and demands of the stakeholder groups need to be harmonized [93]. So far, disagreements on the distribution of entitlements to benefits and profits between the different stakeholder groups can be observed (Table 1). The two potential adopters of

Aquaculture and Renewable Energy Systems, Integration of. Table 1 Offers, needs, and constraints characteristics of mariculture operators and offshore wind farmers concerning O&M activities. Interrelated aspects between the two actor groups are indicated in bold (modified after [86])

Characteristics	Actor groups	
	Wind farmers	Mariculture operators
		
Offers	• Fixed offshore infrastructure • Logistic platform • Financial support (EEG amendment)	• Upgradeable sea-going vessels • Offshore mentality • Offshore skills and experience
Needs	• Specialization of equipment (construction vs hire; “marinization” of onshore equipment) • Specialization of personnel • Sea-going vessels • Service demands (man-hours) • Suitable O&M pattern (corrective vs preventive maintenance) • Suitable O&M pattern (opportunity vs periodic maintenance)	• Specialization of equipment (construction vs alteration of existing oil industry/fishery vessels) • Specialization of personnel • Fixed offshore infrastructure • Technical and logistic support • Service demands (man-hours) • Offshore skills and experience • Offshore mentality
Constraints	• Operation costs • Technical challenges • Distance to farm site • Available working days (estimated 100/year) • Difficult logistics for O&M • Reliability of offshore wind turbines	• Access to farm site (uncertain regulatory and permit requirements) • Distance to farm site • Available working days (estimated 30–100/year) • Difficult logistics for maintenance and harvesting • Reliability of culturing devices

such a multi-use scheme illuminate different sets of skills and capacities in terms of offers, needs, and constraints characteristics. These are vital resources, which provide the basis for forming any sustainable offshore co-management arrangements [85]. Hereby, a fair negotiation and bargaining process is the most essential component to effectively orchestrate co-management of offshore wind farmers and future mariculture operators, such as mussel harvesters. The latter already dispose vital skills and experiences for working in the open sea. Still, working methods have to be adjusted to the offshore culture production mode.

If such an offshore co-management is considered as a network activity between private actors, such as wind farmers or mariculture operators/fishermen and public authorities, one of its basic characteristics is the fact that a third party can coordinate the activities of formally separated parties [94]. Ways and means have to be developed that balance the respective interests of dominant and politically supported wind farming participants with small-scale entrepreneurial mariculturists. The key question is how institutional arrangements could act as "boundary organizations" [95] in an offshore co-management process. Such a process is more likely to develop and succeed if an interface management that acts as moderator, disclosing the interests of the actor groups and offering possibilities for concerted action, guides it. With respect to the decision-making arrangements at the three levels (operational level, organizational level, and legislative level), the interface management would thus help to determine the rules for interaction among the actor groups and state authorities at the organizational level. Besides, it would facilitate organizing and decision making of the day-to-day activities at the operational level. However, to authorize and legitimize new co-management arrangements for interacting offshore O&M activities, new policies must be developed or existing laws amended. Following a dynamic process of forming new institutional structures, the establishment of a communication arena may (a) support a common understanding of the entire co-management process, (b) provide the overall framing for an improved communication among the participating actor groups, (c) increase the level of trust among the actor groups, and (d) promote sustainability and efficiency in times of scarcity of spatial resources [85]. However, top–down induced management schemes by, e.g., the national government, hold a high potential for failure. Involving the relevant actors improves the social acceptability of innovative concepts and their applicability [96]. Consequently, it appears that for developing and implementing a wind farm–mariculture multiple-use concept, co-management, such as that described by Carlsson and Berkes [94], should ideally be carried out with the participation of different actors that typically try to find ways to learn from their actions and adapt the behavior to the consequences of their own and other's actions. This must be supported by the relevant authorities at all levels and must find its way into the legislative framework at the EU and national level.

On EU level, the issue of access to space for maritime activities, including aquaculture, has been recognized in several communications over the past years, e.g., in 2007 pertaining to the Integrated Maritime [97] Policy or in 2009 concerning a new impetus for sustainable aquaculture in Europe. In the latter, all Member States are asked to develop marine spatial planning systems, in which they fully recognize the strategic importance of aquaculture. This Strategy also aims at providing EU leadership and guidance to both stakeholders and administrations to ensure consistency and clarity in designing the necessary policies for the future sustainable development of European aquaculture. In this context, a partnership between public authorities and interested parties at EU, national, and local level play a crucial role.

Hence, European aquaculture should benefit from an improved framework for governance; however, it is stressed that the national authorities have a primary role in shaping aquaculture development in their territory. While in some countries aquaculture is defined and regulated under the agricultural laws, in other countries regulations are dispersed, and consequently the responsibilities are in the hand of several agencies with no clearly defined lead agency. So far, a number of important challenges that limit the development of European aquaculture directly depend on policies and actions taken at national or regional level. A bottom–up approach is therefore needed so that the public authorities can establish an appropriate framework for the vision of multiple-use of offshore areas to become operational. A participatory approach contributes to lifting bottlenecks in national legislation.

This framework needs to be transparent, consistent and cost-effective in order to allow the industry to realize its potential. Unless these and other regulative issues pertaining to multi-use offshore conditions remain unresolved, an establishment of offshore co-management arrangements may be very difficult. Still, the current lack of legislation in the EEZ holds the potential to implement concerted innovative concepts of offshore constructions and thereon-interacting activities.

However, several restrictions are still needed to be resolved. Questions pertaining to access rights within the wind farm area have to be deciphered. So far, approved offshore wind farm territories in, e.g., the German EEZ, are designated as restricted area, prohibiting any kind of public access [98, 99]. However, conveying access rights to a second party is inevitable if wind farm O&M is performed by a commissioned subcontractor and not by the licensee itself. In a wind farm–mariculture multiple-use arena, the same access and user rights have to be guaranteed to a mariculture operator who enters the territory for purposes not related to wind farming but for maintaining culturing devices and harvesting procedures. In this case, precise positioning of aquaculture installations within the wind farm territory as well as access lanes for both parties have to be specified.

In addition, the question of harmonizing the tenure or duration of a lease for offshore resources has to be tackled. If there is, i.e., significant discrepancy in the length of lease tenures between the two uses to be combined, the resource users may not be inclined to create long-term co-management arrangements. Furthermore, cooperative management structures also benefit if the leasing process was combined and/or effectively coordinated, since it facilitates, i.e., integrating O&M within a co-management scheme once the projects are operational.

Yet, in order to define the functional structure of such a co-management regime in detail, reliable outcomes on economic and technical integration prospects of a joint wind farm–mariculture venture have to be produced. The latter is a major research demand, which was voiced by most of the interview partners along the North Sea coast so far [93]. Cumulative impacts of different economic sectors, such as offshore wind farms and mariculture need to be addressed, which provides an opportunity to create synergies between different industrial sectors prior to their installation.

Outcome of Economic Studies

The *Feasibility Study* [13, 24] provided a general overview on market prices, market demands, classification of candidate species as high-value products, and the cost of some infrastructure. The study showed possible market value of offshore aquaculture products in comparison to the performance of existing conventionally operated farms in coastal waters.

Basic data for offshore mussel cultivation in close vicinity to a designated offshore wind farm in the open sea of the German Bight were compiled. It contained different case-scenario calculations to illustrate the impact of changing parameter values on overall profitability or non-profitability of this activity. Primary focus was placed on the production of consumer mussels, but seed mussel cultivation is also taken into consideration. This study concluded with providing some recommendations on how favorable terms or actions could further improve profitability of offshore mussel cultivation. Results intended to shed some light on business management topics that future offshore mariculture operators should follow in order to be efficient [100].

Nontheless, the economics of a joint offshore wind farm–mariculture utilization scheme still remain to be evaluated in more detail.

Future Directions

By setting higher value on an inclusion of stakeholder knowledge and opinions, the initiation of the *Coastal Futures Project* resulted in a stronger focus on the practicability of multifunctional use of offshore areas. It can be shown that such innovative new concepts are highly complex and interdependent. First, results indicate that secure technical and economic feasibility appears to be a basic prerequisite to assure that both offshore wind farm operators and aquaculturists will support the multi-use concept, especially as far as the management of joint activities is concerned.

This suggests that as soon as technical and economic aspects are evaluated in more detail, it is important to initialize a comprehensive communication program to provide information to the key public and private actor groups (stakeholders). Furthermore, effective and continuous participation of all stakeholders on all levels from the very beginning of the multi-use approach must be ensured. This supports the orchestration of scientific and local user knowledge in an overall approach to combine different offshore uses. In addition, it contributes to adding a joint wind farm–mariculture venture to their future portfolio.

More detailed data are needed to calculate the economic potentials and risks of a co-used wind farm area for the production of seafood. Apart from the principal feasibility of an area as an aquaculture site, growth rates and product quality must be predictable. First, results on blue mussels from test areas show that highest product qualities can be expected from testing areas offshore. A proven product quality ensures higher market prizes, should compensate for higher investment costs for the culture systems, and help to install a functioning offshore aquaculture system in the German Bight.

Generall, science for open ocean aquaculture needs a transformative moment. It seems necessary to learn the skills to interact constructively with different scientific disciplines and different stakeholders. This will require a new science for managed marine seascapes [101]. Creating a system biology paradigm in ecosystem science and aquaculture will require a multidisciplinary input, with scientific interactions not just at the margins of each discipline, but focused collaboratively on the realization of a vision of multifunctional, spatially effective, and sustainable use of ocean space. This will require new kinds of scientists (with new kinds of career structures) who are trained to work in multidisciplinary teams. The need for such training is now widely recognized and is reflected in the emerging curricula's of many new MSc courses.

It is mandatory to discover what to do, at what scale, in what modality – engineering, farming, legislation, social organization, economic initiatives, etc. – and how to do it. Since the activities in the ocean realm are concerted in integration, future activities must also be integrated over all these modalities.

Bibliography

1. FAO/FIDI (1989) Aquaculture production (1984–1986) Food and Agriculture Organisation of the United Nations. Rome Fisheries Circular 815, 106
2. FAO (1997) Aquaculture development. Technical guidelines for responsible fisheries. Food and Agriculture Organisation of the United Nations, Rome, pp 5–40
3. EU Commission (2000) On integrated coastal zone management: a strategy for Europe. Communication from the Commission to the Council and the European Parliament, COM (2000) 547 final
4. Garvine R, Kempton W (2008) Assessing the wind field over the continental shelf as a resource for electric power. J Mar Res 66(6):751–773
5. Pauly D, Christensen V, Guénette S, Pitcher TJ, Sumaila RU, Walters CJ, Watson R, Zeller D (2002) Towards sustainability in world fisheries. Nature 418:689–695
6. FAO (2004) The state of world fisheries and aquaculture-2004 (SOFIA). Fisheries Department. Food and Agriculture Organisation of the United Nations, Rome, Italy
7. FAO (2009) The State of World Fisheries and Aquaculture (SOFIA) 2008, FAO Fisheries and Aquaculture Department. Food and Agriculture Organisation of the United Nations
8. Buck BH (2007a) Experimental trials on the feasibility of offshore seed production of the mussels *Mytilus edulis* in the German Bight: installation, technical requirements and environmental conditions. Helgol Mar Res 61:87–101
9. Buck BH (2007b) Marikultur als Co-Nutzung in Offshore-Windparks: Status Quo, Probleme und Perspektiven, Meeresumwelt-Symposium 2006: 16. Symposium, 13. bis 14. Juni 2006, CCH – Congress Center Hamburg/Bundesamt für Seeschifffahrt und Hydrographie in Zusammenarbeit mit dem Bundesumweltamt im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit, pp 167–179
10. FAO (2006) Fishery information, data and statistics unit. Aquaculture production: values 1984–2004. FISHSTAT Plus – universal software for fishery statistical time series. Food and Agriculture Organization of the United Nations, Rome, Italy
11. Burbridge P, Hendrick V, Roth E, Rosenthal H (2001) Social and economic policy issues relevant to marine aquaculture. J Appl Ichthyol 17:194–206
12. Rawski TG, Xiao W (2001) Roundtable on Chinese economic statistics: introduction. Chin Econ Rev 12:298–302
13. Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MCM, Clay J, Folke C, Lubchenco J, Mooney H, Troell M (2000) Effect of aquaculture on world fish supplies. Nature 405:1017–1024
14. Roth E, Ackefors H, Asche F, Balnath C, Black E, Black K, Boghen A, Browdy C, Burbridge P, Castell JD, Chamberlain G, Dabrowski K, Davies I, Dosdat A, Eleftheriou A, Ervik A, Gordin H, Heinig CS, Hilge V, Karakassis I, Kuhlmann H, Landry T, von Lukowicz M, McGlade J, Price A, Rheault RB, Rosenthal H, Saint-Paul U, Sandifer PA, Saroglia M, Silvert W, SteVens W, Soto D, Varadi L, Verreth J, Verdegem M, Waller U (2002) An intellectual injustice to aquaculture development: a response to the review article on "Effect of aquaculture on world fish supplies", Report of the ICES working group on environmental interactions of mariculture, F:04 REF ACME, Annex 4, pp 83–89
15. Buck BH (2004) Farming in a high energy environment: potentials and constraints of sustainable offshore aquaculture in the

German Bight (North Sea). Dissertation. University of Bremen, Germany
16. Davis A, Bailey C (1996) Common in custom, uncommon in advantage: common property, local elites, and alternative approaches to fisheries management. Soc Nat Resources 9:251–265
17. Adger WN, Luttrell C (2000) Property rights and the utilisation of wetlands. Ecol Econ 35:75–89
18. Rana KJ (1997) Aquatic environments and use of species subgroups. In: Review of the state of world aquaculture. FAO Fisheries Circular FIRI/C886 (Rev. 1). Food and Agriculture Organisation (FAO), Rome, Italy, pp 7–16
19. Lee PG, Turk PE (1998) Overview of a modern, shore-based hatchery for offshore mariculture support. In: Stickney RR (ed) Joining forces with industry – open ocean aquaculture. Proceedings of the third annual international conference, May 10–15, Texas Sea Grant College Program, Corpus Christi, pp 87–102
20. Krause G, Buck BH, Rosenthal H (2003) Multifunctional use and environmental regulations: potentials in the offshore aquaculture development in Germany. Proceedings of the multidisciplinary scientific conference on sustainable coastal zone management "Rights and duties in the coastal zone", 12–14 June 2003. Stockholm, Sweden
21. Buck BH, Krause G, Rosenthal H, Smetacek V (2003) Aquaculture and environmental regulations: the German situation within the North Sea. In: Kirchner A (ed) International marine environmental law: institutions, implementation and innovation, vol. 64. International Environmental. Law and Policies Series of Kluwer Law International, The Hague, pp 211–229
22. Firestone J, Kempton W, Krueger A, Loper CE (2004) Regulating offshore wind power and aquaculture: messages from Land and sea. Cornell J Law Public Policy 14(1):71–111
23. Langan R (2009) Co-location of offshore energy and seafood production: potential synergies, compatibilities and conflicts. Conference paper, the ecology of marine wind farms: perspectives on impact mitigation, siting, and future uses, 8th annual Ronald C. Baird Sea Grant Science Symposium, November 2–4 2009, Newport, Rhode Island
24. BMU (2006) Integriertes Küstenzonenmanagement in Deutschland (IKZM). Nationale Strategie mit Bestandsaufnahme nach der EU-Empfehlung 2002/413/EG. Bundesregierung für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
25. Kannen A (2004) Holistic systems analysis for ICZM: the Coastal Futures approach. In: Schernewski G, Dolch T (eds) Geographie der Meere und Küsten. Coastline reports, vol 1, pp 171–181
26. Buck BH (2002) Open Ocean Aquaculture und Offshore-Windparks: Eine Machbarkeitsstudie über die multifunktionale Nutzung von Offshore-Windparks und Offshore-Marikultur im Raum Nordsee. Reports on Polar and marine research. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, pp 412–252
27. Ryan J (2005) Offshore aquaculture – do we need it, and why is it taking so long? International Salmon Farmers Association (Ireland). Expert workshop on sustainable aquaculture, DG JRC European Commission, Institute for Prospective Technological Studies, 17–18 January 2005. Seville, Spain
28. Dahle LA, DePauw N, Joyce J (1991) Offshore aquaculture technology – possibilities and limitations. Aquacult Environ 14:83–84
29. Eleftheriou M (1997) Aqualex: a glossary of aquaculture terms. Wiley-Praxis series in aquaculture and fisheries, Aqualex Multimedia Consortium Ltd
30. Chopin T (2009) Let's not move just the fish to the open ocean. . . an integrated multi-trophic aquaculture approach should not be an afterthought for 2050. Conference paper, the ecology of marine wind farms: perspectives on impact mitigation, siting, and future uses, 8th annual Ronald C. Baird Sea Grant Science Symposium, November 2–4, 2009, Newport, Rhode Island
31. Dena (2007) Renewable energies: Germany's first test Weld for offshore wind energy. Dena fact sheet. German Energy Agency, Berlin
32. Tiedemann A (2003) Windenergieparke im Meer – Perspektiven für den umweltverträglichen Einstieg in eine neue Großtechnologie. In: Lozán J, Rachor E, Reise K, Sündermann J, Westernhagen HV (eds) Warnsignale aus Nordsee & Wattenmeer: Eine aktuelle Umweltbilanz. Wissenschaftliche Auswertungen, Hamburg, pp 142–148
33. BMU/SOW (2007) Offshore wind power deployment in Germany. In: Rehfeldt K, Paschedag U, Bömer J (eds) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and Stiftung der Deutschen Wirtschaft zur Nutzung und Erforschung der Windenergie auf See/Offshore Wind Energy Foundation (SOW). Scholz-Druck GmbH, Dortmund, pp 31
34. Gierloff-Emden HGR (2002) Wandel der Umwelt der See-und Küstenlandschaft der Nordsee durch Nutzung von Windenergie. Mitteilungen der Österreichischen Geographischen Gesellschaft 144:219–226
35. Dahlke V (2002) Genehmigungsverfahren von Offshore-Windenergieanlagen nach der Seeanlagenverordnung. Natur und Recht 24:472–479
36. BWE (2008) Datenblatt 2007: Datenblatt Windenergie 2007. Bundesverband WindEnergie
37. GWEC (2007) Continuing boom in wind energy – 20 GW of new capacity in 2007. Press release 15/02 200. Global Wind Energy Council
38. BSH (2010) Wind farms. Bundesamt für Seeschifffahrt und Hydrographie. Federal Maritime and Hydrographic Agency, Hamburg/Rostock
39. Ventus A (2010) Der erste deutsche Offshore-Windpark (first german offshore wind farm). Deutsche Offshore-Testfeld und Infrastruktur. GmbH & Co. KG, Oldenburg
40. BWE (2007) Offshore Windenergie. BWE Hintergrundpapiere. Bundesverband WindEnergie

41. Wirtz KW, Tol RSJ, Hooss KG (2003) Mythos "Offene See": Nutzungskonflikte im Meeresraum. In: Lozan L et al (eds) Warnsignale aus Nordsee & Wattenmeer. Eine aktuelle Umweltbilanz. Wissenschaftliche Auswertungen, Hamburg, pp 157–160
42. Buck BH, Krause G, Rosenthal H (2004) Multifunctional use, environmental regulations and the prospect of offshore co-management: potential for and constraints to extensive open ocean aquaculture development within wind farms in Germany. Ocean Coast Manage 47:95–122
43. Jentoft S (2000) Co-managing the coastal zone: is the task too complex? Ocean Coast Manage 43:527–535
44. Michler-Cieluch T (2009) Co-Management processes in integrated coastal management: the case of integrating marine aquaculture in offshore wind farms. PhD thesis, University of Hamburg, Germany
45. Führböter A, Dette HH (1983) Wasserstände, Wind und Seegang im Seegebiet um Helgoland in den Jahren von 1969 bis 1983. Leichtweiß-Institut für Wasserbau der TU Braunschweig, Bericht Nr, 577
46. Becker G, Dick S, Dippner J (1992) Hydrography of the German Bight. Mar Ecol Prog Ser 91:9–18
47. Buck BH, Berg-Pollack A, Assheuer J, Zielinski O, Kassen D (2006) Technical realization of extensive aquaculture constructions in offshore wind farms: consideration of the mechanical loads. In: Proceedings of the 25th international conference on offshore mechanics and Arctic engineering, OMAE 2006: presented at the 25th International conference on offshore mechanics and Arctic engineering, 4–9 June 2006, Hamburg, Germany/American Society of Mechanical Engineers, pp 1–7
48. Takayanagi K (1998) Water quality guidelines for aquaculture: an example in Japan. In: Howell WH, Keller BJ, Park PK, McVey JP, Takayanagi K, Uekita Y (eds) Nutrition and technical development of aquaculture. Proceedings of the 26th US–Japan aquaculture symposium, Durham/New Hampshire/USA September 16–18, 1997. UJNR technical report No. 26, Durham, University of New Hampshire Sea Grant Program, pp 247–254
49. BSH (2006) MURSYS – marine environment reporting system information from the North Sea and Baltic Sea. Bundesamt für Seeschifffahrt und Hydrographie (BSH), Hamburg
50. Stickney RR (1998) Joining forces with industry – open ocean aquaculture. Proceedings of the 3rd annual international conference, May 10–15, Corpus Christi. TAMU-SG-99–103, Corpus Christi, Texas Sea Grant College Program
51. Bridger CJ, Costa-Pierce BA (2003) Open ocean aquaculture: from research to commercial reality. The World Aquaculture Society, Baton Rouge
52. Michler-Cieluch T, Kodeih S (2008) Mussel and seaweed cultivation in offshore wind farms: an opinion survey. Coast Manage 36(4):392–411
53. Buck BH, Buchholz CM (2004) The offshore-ring: a new system design for the open ocean aquaculture of macroalgae. J Appl Phycol 16:355–368
54. Buck BH, Walter U, Liebezeit G (2011) Larval occurrence and settlement in the German Bight: A trial to estimate potentials for *Mytilus edulis* culture in offshore areas, Helgoland Marine Research (in press)
55. BSH (2009) Bundesamt für Seeschifffahrt und Hydrographie – BSH (Federal Maritime and Hydrographic Agency), CONTIS-Geodata. Hamburg/Rostock
56. Hickman RW (1992) Mussel cultivation. In: Gosling E (ed) The mussel *Mytilus*: ecology, physiology, genetics and culture, vol 25, Development in aquaculture and fisheries science. Elsevier, Amsterdam, pp 465–510
57. Critchley AT, Ohno M, Largo DB (2006) World seaweed resources. An authoritative reference system. ETI BioInformatics. DVDROM
58. Tseng CK (1989) *Laminaria* mariculture in China. In: Doty MS, Caddy JF, Santelices B (eds) Case studies of seven commercial seaweed resources. FAO Fisheries Technical Paper – 281. Food and Agriculture Organization of the United Nations (FAO), Rome
59. Strathmann MF (1987) Reproduction and development of marine invertebrates of the northern Pacific Coast. University of Washington Press, Seattle, pp 670
60. Pulfrich A (1997) Seasonal variation in the occurrence of planktic bivalve larvae in the Schleswig-Holstein Wadden Sea. Helgol Wiss Meer 51:23–39
61. Walter U, Liebezeit G (2001) Abschlußbericht des Projektes: Nachhaltige Miesmuschel-Anzucht im niedersächsischen Wattenmeer durch die Besiedlung natürlicher und künstlicher Substrate. Forschungszentrum Terramare, pp 1–97
62. Walter U, Liebezeit G (2003) Efficiency of the blue mussel (*Mytilus edulis*) spat collectors in highly dynamic tidal environments of the Lower Saxonian coast (Southern North Sea). Biomol Eng 20:407–411
63. Scarratt D (1993) A handbook of northern mussel culture. Island Press, Montague, pp 167
64. Gosling E (2003) Bivalve molluscs: biology, ecology and culture. Blackwell Publishing/MPG Books, Bodmin/Cornwall, pp 443
65. Brenner M (2009) Site selection criteria and technical requirements for the offshore cultivation of blue mussels (*Mytilus edulis* L.). PhD thesis, School of Engineering and Science, Jacobs University, Bremen, pp 151
66. Langan R, Horton F (2003) Design, operation and economics of submerged longline mussel culture in the open ocean. Bull Aquacult Assoc Can 103:11–20
67. Neushul M, Harger BWW (1985) Studies of biomass yield from a near-shore macroalgal test farm. J Solar Energy Eng 107:93–96
68. Neushul M, Benson J, Harger BWW, Charters AC (1992) Macroalgal farming in the sea: water motion and nitrate uptake. J Appl Phycol 4:255–265
69. Turner R (2001) Offshore mariculture: site evaluation. In: Muir J, Basurco B (eds) Options méditerranéennes – Mediterranean offshore mariculture. Etudes et recherches, Serie B, Numéro 30, Zaragoza, CIHEAM, INO Reproducciones, pp 141–157

70. Pérez OM, Telfer TC, Ross LG (2003) On the calculation of wave climate for offshore cage culture site selection: a case study in Tenerife (Canary Islands). Aquacult Eng 29:1–21
71. Dalton R (2004) Fishing for trouble. Nature 431:502–504
72. Naylor R, Burke M (2005) Aquaculture and ocean resources: raising tigers of the sea. Annu Rev Environ Res 30:185–218
73. Allen JI, Moore MN (2004) Environmental prognostics: is the current use of biomarkers appropriate for environmental risk evaluation. Mar Environ Res 58:227–232
74. Buck BH, Walter U, Rosenthal H, Neudecker T (2006) The development of mollusc farming in Germany: past, present and future, World Aquaculture 37(2):6–11 & 66–69
75. Buck BH, Thieltges D, Walter U, Nehls G, Rosenthal H (2005) Inshore–offshore comparison of parasite infestation in *Mytilus edulis*: implications for open ocean aquaculture. J Appl Ichthyol 21:107–113
76. Brenner M, Buck BH, Koehler A (2007) New concept combines offshore wind farms, mussel cultivation. Global Aquacult Advocate 10:79–81
77. Buck BH, Buchholz CM (2005) Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. Aquaculture 250:674–691
78. Manefeld T (2006) Ansiedlungspotential von Miesmuschellarven (*Mytilus edulis*) an verschiedenen Substraten freihängender Brutkollektoren. Thesis, University of Applied Sciences Bremerhaven, Germany
79. Voss D (2006) Parasitierungsgrad der Miesmuschel (*Mytilus edulis*) in Abhängigkeit zur Tiefenzonierung und Entfernung zur Küste. Thesis, University of Applied Sciences Bremerhaven, Germany
80. Brenner M, Buck BH (2010) Attachment properties of blue mussel (*Mytilus edulis L.*) byssus threads on culture-based artificial collector substrates. Aquacult Eng 42:128–139
81. Zielinski O, Assheuer J, Berg-Pollack A, Buck BH, Geisen M, Henkel R, Kassen D (2006) Assessment of mechanical loads and environmental conditions for extensive aquaculture constructions within offshore wind farms: First results from the AquaLast study site. Proceedings of DEWEK 2006: presented at the DEWEK 2006, 22–23 November 2006, Bremen, Germany, pp 1–4
82. Bard (2010) Offshore wind farms. Bard Engineering GmbH. Emden, Germany
83. OFT (2010) *Aquapod* – a submergible fish cage. Ocean Farm Technologies, Searsmont
84. Ostrom E, Burger J, Field CB, Norgaard RB, Policansky D (1999) Revisiting the commons: local lessons, global challenges. Science 284(4512):278–282
85. Hardin G (1968) The tragedy of the commons. Science, 162. Reprinted in Dryzek JS, Schlosberg D (1999) Debating the Earth: the environmental politics reader. Oxford University Press, New York
86. Michler-Cieluch T, Krause G, Buck BH (2009) Reflections on integrating operation and maintenance activities of offshore wind farms and mariculture. Ocean Coast Manage 52(1):57–68
87. Buck BH, Krause G, Michler-Cieluch T, Brenner M, Buchholz CM, Busch JA, Fisch R, Geisen M, Zielinski O (2008) Meeting the quest for spatial efficiency: progress and prospects of extensive aquaculture within offshore wind farms. Helgol Mar Res 62:269–281
88. EU Commission (2009) Building a sustainable future for aquaculture. A new impetus for the Strategy for the Sustainable Development of European Aquaculture. The European Parliament and the Council, COM(2009) 162 final
89. McVey JP (1996) Overview of offshore aquaculture. In: Polk M (ed) Open ocean aquaculture. Proceedings of an international conference, May 8–10, Portland, Maine. New Hampshire/Maine Sea Grant College Program, pp 13–18
90. Braginton-Smith B, Messier RH (1997) Design concepts for integration of open ocean aquaculture and Osprey TM Technology. In: Howell WH, Keller BJ, Park PK, McVey JP, Takayanagi K, Uekita Y (eds) Proceedings of the twenty-sixth US–Japan aquaculture symposium, Durham, New Hampshire. UJNR Technical Report No. 26. University of New Hampshire Sea Grant Program, Durham, pp 239–245
91. Bussel van GJW, Zaaijer MB (2007) Reliability, availability and maintenance aspects of large-scale offshore wind farms, a concepts study. In: Proceedings of MAREC 2001. Delft University of Technology, The Netherlands, pp 119–126
92. Musial W, Butterfield S, Ram B (2006) Energy from offshore wind. In: Proceedings of the offshore technology conference (OTC), 1–4 May, Houston, 11 pp
93. Michler-Cieluch T, Krause G (2008) Perceived concerns and possible management strategies for governing 'wind farm–mariculture integration'. Marine Policy 32(6): 1013–1022
94. Carlsson L, Berkes F (2005) Co-management: concepts and methodological implications. J Environ Manage 75: 65–76
95. Cash DW, Moser SC (2000) Linking global and local scales: designing dynamic assessment and management processes. Global Environ Change 10:109–120
96. Heinelt H (2002) Achieving sustainable and innovative policies through participatory governance in a multi-level context. In: Heinelt H, Getimis P, Kafkalas G, Smith R, Swyngedouw E (eds) Participatory governance in multi-level context. Leske + Budrich, Opladen, pp 17–32
97. EU Commission (2007) An Integrated Maritime Policy for the European Union. Commission Staff Working Document, Accompanying document to the Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions, SEC (2007) 1278
98. Dietz T, Ostrom E, Stern PC (2003) The struggle to govern the commons. Science 302(5652):1907–1912
99. Steins NA, Edwards VM (1999) Synthesis: platforms for collective action in multiple-use common-pool resources. Agric Hum Values 16(3):309–315

100. Buck BH, Ebeling M, Michler-Cieluch T (2010) Mussel cultivation as a co-use in offshore wind farms: potential and economic feasibility. Aquacult Econ Manage 14(4): 1365–7305
101. Bradbury RH, Seymour RM (2009) Coral reef science and the new commons. Coral Reefs 28:831–837

Aquaculture, Ecological

BARRY A. COSTA-PIERCE
Graduate School of Oceanography, Rhode Island Sea, Grant College Program, University of Rhode Island, URI Bay Campus, Narragansett, RI, USA

Article Outline

Glossary

Biofloc A mixture of detritus, bacteria, and other microscopic organisms that aggregates in flocs, which are used for controlling water quality and enhancing the delivery of natural foods to omnivorous species in aquaculture.

Ecosystem An area of the natural environment in which the structure and functions of the physical (rocks, soil, etc.) and natural (all living organisms) environments are considered together in interacting food webs.

Escapees The unintended releases of cultured organisms from captivity into the wild.

Polyculture The practice of making compatible the culture of multiple species in the same physical space by stocking or planting organisms having different food, spatial, or temporal niches.

Resilience The ability of a natural or aquaculture system to absorb abrupt changes or disturbances without collapsing. A resilient aquaculture ecosystem can withstand physical and economic shocks and rebuild itself.

Stewardship An ethic that engages all affected stakeholders in the cooperative planning and management of the environmental quality to prevent degradation and facilitate recovery in the interest of long-term sustainability.

Watershed An area of land where all of the water that is under it or drains off of it goes into the same place.

Definition of Ecological Aquaculture

Ecological aquaculture is an alternative model of aquaculture development that uses ecological principles as the paradigm for the development of aquaculture [1, 2]. Ecological aquaculture plans, designs, develops, monitors, and evaluates aquatic farming ecosystems that preserve and enhance the form and functions of the natural and social environments in which they are situated. Ecological aquaculture farms are integrated "aquaculture ecosystems" designed to deliver both economic and social profit (Fig. 1).

Ecological aquaculture incorporates at the outset – and not as an afterthought – planning for not only the sustainable production of aquatic foods, but also for innovation [3], community development, and the wider social, economic, and environmental contexts of aquaculture at diverse scales, both large and small, and at the commercial, school, and homeowner scales [4, 5]. Ecological aquaculture also uses the "aquaculture toolbox" [6] to play vital roles in non-food, natural ecosystem rehabilitation, reclamation, and enhancement.

Introduction

The roots of ecological aquaculture are in Asia [7, 8]. In this century, however, Asia, especially China, during the period from 1980s to present has chosen the industrial model of aquaculture development, and has dismantled much of its rich ecological aquaculture heritage, and choosing instead to intensify and import vast quantities of feedstuffs. As a result of intensification and the use of imported feeds, freshwater