Bela H. Buck · Richard Langan *Editors*

Aquaculture Perspective of Multi-Use Sites in the Open Ocean

The Untapped Potential for Marine Resources in the Anthropocene

Springer Open

Aquaculture Perspective of Multi-Use Sites in the Open Ocean

Bela H. Buck · Richard Langan
Editors

Aquaculture Perspective of Multi-Use Sites in the Open Ocean

The Untapped Potential for Marine Resources in the Anthropocene

Springer Open

Editors
Bela H. Buck
Marine Aquaculture, Maritime Technologies and ICZM
Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI)
Bremerhaven
Germany

Richard Langan
School of Marine Science and Ocean Engineering
University of New Hampshire
Durham, NH
USA

ISBN 978-3-319-51157-3 ISBN 978-3-319-51159-7 (eBook)
DOI 10.1007/978-3-319-51159-7

Library of Congress Control Number: 2016960276

Cover illustration: Extractive Aquaculture in a German Wind Farm by Alexandra Haasbach.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Chapter 3
Technological Approaches to Longline- and Cage-Based Aquaculture in Open Ocean Environments

Nils Goseberg, Michael D. Chambers, Kevin Heasman, David Fredriksson, Arne Fredheim and Torsten Schlurmann

Abstract As the worldwide exploitation rate of capture fisheries continues, the development of sustainable aquaculture practices is increasing to meet the seafood needs of the growing world population. The demand for aquatic products was historically satisfied firstly by an effort to expand wild catch and secondly by increasing land-based and near-shore aquaculture. However, stagnation in wild catch as well as environmental and societal challenges of land-based and near-shore aquaculture have greatly promoted efforts to development farming offshore technologies for harsh, high energetic environments. This contribution thus highlights recent technological approaches based on three sample sites which reach out from sheltered near-shore aquaculture sites to sites with harsh wave/current conditions. It compares and evaluates existing technological approaches based on a broad literature review; on this basis, we then strongly advocate for presently available aquaculture technologies to merge with future offshore structures and platforms and to unveil its added value through synergetic multi-use concepts. The first example

N. Goseberg (✉)
Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Leibniz Universität Hannover, Nienburger Str. 5, 30167 Hannover, Germany
e-mail: goseberg@fi.uni-hannover.de

M.D. Chambers
School of Marine Science and Ocean Engineering, University of New Hampshire, Morse Hall, Room 164, Durham, NH, USA

K. Heasman
Cawthron Institute, Private Bag 2, Nelson 7010, New Zealand

D. Fredriksson
Department of Naval Architecture and Ocean Engineering, United States Naval Academy, Annapolis, MD, USA

A. Fredheim
Department of Aquaculture Technology, SINTEF Fisheries and Aquaculture, P.O. Box 4762, 7465 Sluppen, Trondheim, Norway

T. Schlurmann
Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Leibniz Universität Hannover, Nienburger Str. 4, 30167 Hannover, Germany

B.H. Buck and R. Langan (eds.), *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, DOI 10.1007/978-3-319-51159-7_3

describes the recent development of longline farming in offshore waters of New Zealand. New Zealand has designated over 10,000 ha of permitted open ocean water space for shellfish farming. The farms range from 8 to 20 km out to sea and a depth of 35–80 m of water. Research has been ongoing for the last 10 years and the first commercial efforts are now developing in the Bay of Plenty. New methods are being developed which should increase efficiency and reduce maintenance with a particular focus on Greenshell mussel (*Perna canaliculus*) and the Pacific Oyster (*Crassostrea gigas*), Flat Oyster (*Tiostrea chilensis*) and various seaweeds. The second case study involves a long-term, open ocean aquaculture (OOA) research project conducted by the University of New Hampshire. During the course of approximately 10 years, the technological aspects of OOA farming were conducted with submersible cages and longlines, surface feeding systems and real time environmental telemetry. The grow-out potential of multiple marine species such as cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), halibut (*Hippoglossus hippoglossus*), blue mussel (*Mytilus edulis*), sea scallop (*Placopecten magellanicus*) and steelhead trout (*Oncorhynchus mykiss*) were investigated at a site 12 km from shore. The last study presents a multi-use aspect of aquaculture for an open ocean site with fish cages attached to existing offshore wind energy foundations. Technological components such as mounting forces and scour tendencies of two different cage structures (cylindrical and spherical) were investigated by means of hydraulic scale modeling. The cages were pre-designed on the basis of linear theory and existing standards and subsequently exposed to some realistic offshore wave conditions. The wind farm “Veja Mate” in German waters with 80 planned 5 MW turbines anchored to the ground by tripiles is taken as the basis for the tested wave conditions. Based on findings stemming from the three example approaches conclusions are drawn and future research demand is reported.

3.1 Introduction

As the worldwide exploitation rate of capture fisheries continues, the development of sustainable aquaculture practices is increasing to meet the seafood needs of the growing world population. The demand for aquatic products was historically satisfied firstly by an effort to expand wild catch and secondly by increasing land-based and near-shore aquaculture. However, stagnation in wild catch as well as environmental and societal challenges of land-based and near-shore aquaculture have greatly promoted efforts to development farming offshore technologies for harsh, high energetic environments. As a consequence, ocean domestication is of key importance to maintain the ocean as a sustainable source of food, both economically and ecologically (Marra 2005).

While the annual growth rate of aquaculture production has been 6.3%, total aquaculture production grew from 34.6 million tons in 2001 to 59.9 million tons in 2010; thus it depicts the second important sector to supply the continued global demand for marine proteins (FAO 2012). In 2010, world marine farming production was estimated at 36.1 million tons with a value of US$37.9 billion (FAO 2012). Nearly all ocean farming is conducted inshore, in contrast to offshore aquaculture that is still in its infancy. Offshore aquaculture may be defined as taking place in areas of the open ocean exposed to significant wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time (Drumm 2010).

There is an obvious, demand-driven need to develop offshore aquaculture throughout the world. However, one of the most difficult obstacles to overcome is finding locations for new aquaculture farms. Because of the difficulties associated with inshore locations, it is assumed that most new aquaculture activities will be developed offshore in the Exclusive Economic Zone (3–200 miles) where there are fewer conflicts with existing user groups, and less risk of pollution. The high energy (winds and waves) of such exposed locations, however, present significant technical challenges in the design, testing and construction of aquaculture systems that are capable of surviving in these areas. In addition to these technical challenges, there are many biological, regulatory, social and economic problems to be solved.

Despite, drivers at local and global levels provide impetus for aquaculture to move to these unprotected waters of the open sea. There are issues of competition for space with other users, problems with water quality, and oftentimes there is a negative public perception of aquaculture's environmental and aesthetic impacts (Kapetsky et al. 2013). Some of these conflicting issues are also common to the offshore wind energy and oil industry. The oil/gas industry has a long history of installed facilities in offshore locations. The recent pressure to reduce carbon dioxide emissions has additionally leveraged the worldwide planning and installation of offshore wind energy converters. Countries bordering the North and Baltic Sea with limited accessibility of inland building sites such as Denmark, Great Britain or Germany started exploring offshore wind energy feasibility in the end of the eighties (Hau and von Renouard 2006). High energy cost and natural disasters facilitated this development. It is thus natural to assess if foundation structures (piles, tripods, jackets) of existing or licensed wind energy sites could be co-used for additional economic activities such as offshore aquaculture.

Aquaculture migration towards offshore sites has undergone substantial progress in the last two decades. This progress was leveraged by advances in numerical and physical modelling of various fish cages or long line arrangements as well as by technological developments and prototype sites. In order to design an open ocean aquaculture test site near the south of the Isles of Shoals, New Hampshire a numerical model was used by Tsukrov et al. (2000) to optimize the structure. Finite element analysis was applied to study the performance of surface and submerged constructions and a simplified formulation for the simulation of the nets is presented. An improved formulation was presented by Tsukrov et al. (2003) offering a consistent net element which is generally capable to model fluid action and net inertia of fishing nets and allows to simulate environmental loadings originating from currents, waves or other mechanical impacts. Motivated by the impact of storm-waves to aquaculture facilities, a lump-mass method was used to study to the effects of currents to net-cage systems and good agreement was found between the numerical results and prior experimental findings (Huang et al. 2006).

Experimental studies most often provide the basis for numerical modelling attempts, help calibrating numerical models and verify achieved simulation results. Experimental research offers down-scaled, controllable and repeatable conditions for reliable analysis which becomes increasingly important as study sites move from more sheltered near-coast regions to high-energetic offshore sites. The effects of current-only conditions on down-weighed flexible circular nets were investigated in greater detail experimentally by Lader and Enerhaug (2005). They emphasized that forces on and deformations of flexible nets are mutually highly dependent on each other. This in particular applies to aquaculture sites residing in the open ocean with harsh environments. The suitability of a modified gravity-type fish cage was similarly investigated by experimental and numerical means under exposed environmental conditions with regular waves (DeCew et al. 2005). These controlled wave conditions allowed for the derivation of motion response in heave, surge and pitch as well as load response in the anchor and bridle lines. The findings were then extended to the irregular regime by the application a stochastic approach. Based on a combination of numerical and experimental approaches Huang et al. (2008) conjectures aquaculture activities should not be situated waters with current velocities above 1 m/s unless volume-reducing effects can be safely restricted by technological means. At the same time it is recommended to carefully consider the combined effects of currents and obliged waves before facilities are installed at new sites.

Although the tendency to aquaculture site located further off the shore is well traceable in literature there are generally much fewer sources which explicitly focus on the combination of different aquaculture applications at one location or even inclusion of non-aquaculture elements such as support structures from other industries in the open ocean. Buck and Buchholz (2005) discussed the co-use of existing or planned offshore structures for the growth of *Laminaria saccharina* by comparing drag forces measured in a current flume with those resulting from conditions in the North Sea. The authors also reported on the development of a devices to culture macroalgae in a range of offshore conditions (Buck and Buchholz 2004). Based on the analysis of the current development inside the continental shelf around the world Lacroix and Pioch (2011) plead innovative efforts to move towards eco-engineered structures such as artificial fishing reefs or the incorporation of secondary purposes within wind farms. The mutual benefits of wave energy converter foundations as artificial reefs were examined for a building site about 100 km north of Gothenburg at the Swedish coast (Langhamer and Wilhelmsson 2009). It was found that basically the amount of fish and crab on the ground of the foundations was considerably increase whereas the abundance of fish in the water column above was not substantially altered. Another example of the multi-use idea is the development of artificial reefs which oftentimes serve not only the purpose to provide valuable habitat to marine species but also serve as one additional form of coastal protection (Liu and Su 2013).

This contribution presents recent technological advances and innovative approaches towards aquaculture production in harsher oceanic conditions on the basis of three case studies involving the idea of multi-use. The recent advancements of tools and methods to study the response of aquaculture technology to environmental loading such as winds, waves, currents and other mechanical impacts describe above serve as the basis for the presented studies. Technological challenges and existing obstacles due to the high-energetic environment are discussed at the end. Within the first two case studies, currently available potential and challenges of aquaculture is discussed in light of its applicability towards harsher environments and high-energy impacts from winds and waves. Then, we extend our analysis and the conclusions drawn from those first two case studies and present a unique third case study. Therein, existing aquaculture cage technology is thoroughly tested as it is innovatively attached to a commonly used offshore wind energy converter foundation, called a tripile foundation. For the first time, such a multi-use concept was tested under laboratory conditions with valuable conclusions and inter-comparisons between existing and anticipated offshore technologies being reported in the discussion and conclusion chapter.

3.2 Case Study on Long Lines

3.2.1 Mussel Farming Development in NZ

Mussels (the Greenshell™ mussel, *Perna canaliculus*) are the main shellfish in both mass and value to be farmed in New Zealand. They have been farmed in sheltered and semi-sheltered areas since the industry started in 1979. The current production has fluctuated between 86,000 and 101,000 ton per annum between 2011 and 2014. Mussels are farmed using the New Zealand longline system, the general structure of which is discussed below. There are variations to this theme depending on location and farmer preference.

In 2003 consents for the offshore aquaculture space were lodged and the process of obtaining this space started. There were numerous reasons for the departure from the sheltered waters including user conflict and a desire to increase farm size. The proposed farms were in waters ranging from 6 to 20 km off the coast in water depths ranging from 35 to 80 m.

In 2005, the first experimental ropes were installed into the open ocean waters of Hawkes Bay. The first open ocean structure was based on the traditional mussel backbone but it was influenced by the systems used in the Coromandel in the North Eastern corner of New Zealand North Island. The Coromandel generally has higher energy than that of other culture sites such as the Marlborough Sounds.

A traditional inshore New Zealand mussel longline consists of: a mooring; chain; warp; bridal; backbone; bridal; warp; chain and mooring (Fig. 3.1). The early moorings were Danforth type anchors. These were overtaken in preference by

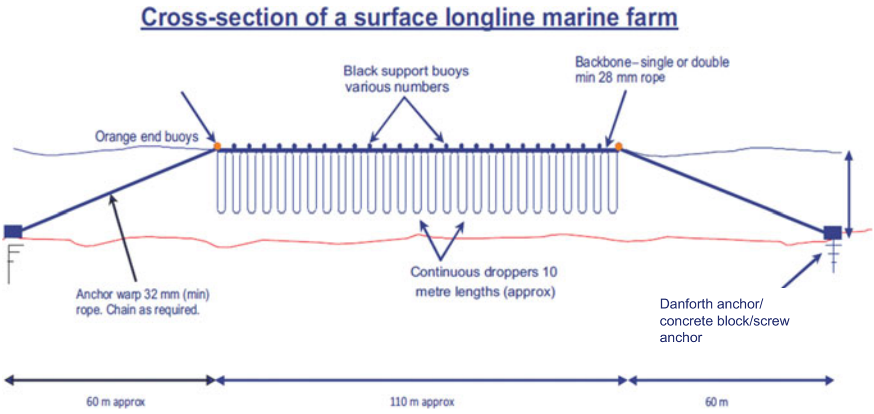

Fig. 3.1 Cross section of a New Zealand surface longline *Credit* New Zealand Marine Farmers Association

concrete shaped moorings of up to 10 metric tons (22,200 lb.) in mass. Where possible concrete mooring are being superseded by screw anchors when new ropes are being installed and the substrate is suitable.

The chain is a heavy duty chain of 6 m (20 ft.) to 15 m (50 ft.) in length. A synthetic rope of 27 mm (>1 in.) to 36 mm (1½ in.) called a warp is attached to the chain and rises to the bridal. The warp is generally three times the depth of the water. The bridal splits into two, each split attaching to a header rope on the opposite edges of the float line, respectively. This section of the mussel longline holding the buoys or floats is called the backbone. Since this backbone has a header rope on each side of the float to support the production line it is referred to as a "double backbone". The backbone extends to the opposite bridal and so on. The buoys are 1.3 m across ($\sim$4 ft. 3 in.) and spaced appropriately to support the mass of growing mussels on the backbone. Typically the backbone ranges from 100 m (328 ft.) to 200 m (656 ft.) long. A mussel longline (production rope) is hung from the backbone. It is attached on one side, descends down to 10 or 15 m, loops up to the opposite side of the backbone and crosses the gap between the buoys and the descends down again. Each loop being approximately 50 cm (20 in.) to 70 cm (28 in.) apart along the backbone. In this way, between 3000 m (9842 ft.) and 4000 m (13,123 ft.) of mussel long line is hung from a 100 m backbone.

The longline hanging from the backbone can produce between 6.5 kg (14 lb. 5 oz.) to 13 kg (28 lb. 10 oz.) per meter (or 4 lb. 12 oz. per ft. to 9 lb. 8 oz. per ft.) depending on site and situation. The time period to produce this would range from 12 to 20 months, again depending on site and location.

As the industry changed from inshore to more exposed sites the backbones were cut down to a single header rope (single backbone) i.e. there is no bridal and the warp joined directly to the backbone (Fig. 3.2) and the production longline is draped in loops along the single header rope or backbone. The backbone is submerged and has approximately 66% of the floatation attached directly to it.

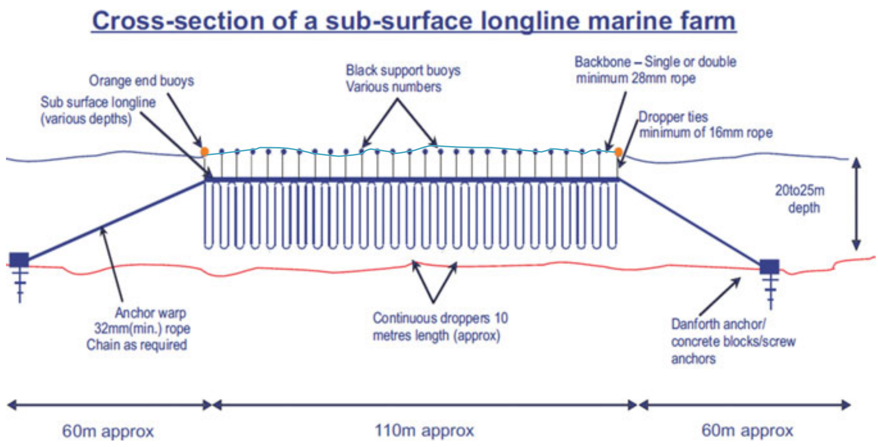

Fig. 3.2 Cross section of a New Zealand subsurface longline. *Note* More recent systems have more floats on the submerged part of the longline *Credit* New Zealand Marine Farmers Association

Additional floatation is positioned on the surface with strops extending from the surface floats to the backbone. The length of the strop dictates the depth of the backbone.

The surface floats will provide 30–40% of the floatation and also give some indication of the load the backbone is bearing and when additional floatation will be required. The backbone is installed loose enough so that a hook can be lowered from a vessel to snag the backbone and the resultant apex of the snagged backbone brought to the surface. The spacing between the droppers may be increased when compared to the inshore systems and may be as much as 1 m (3 ft. 3 in.) apart. By submerging the ropes, this system provides some protection from the wave energy experienced in open ocean situations, however, the surface floats still transfer energy to the backbone which can result in production losses and increased maintenance. In addition, there is an issue arising from the additional requirement in flotation as a result of mussel growth, i.e. once the farm has a large number of backbones on it the management of floatation will increase significantly.

There is no doubt that new systems will be developed in the future. The next generation system that is currently being developed and tested is the "Set and Forget" (S&F) system. This system, developed by the Cawthron Institute (www.cawthron.org.nz) in conjunction with an open ocean farming operation and Government funding (MBIE and Kiwinet), is a fully submersible double backbone system which will be deployed and recovered from the surface.

The S&F system (Fig. 3.3) has a similar configuration to the surface double backbone but where the bridal meets the backbone, there is a mooring directly below it (screw anchor). There are additional intermediate anchors spaced every 35 m along the backbone. These intermediate moorings are threaded through a mechanism in the S&F buoy. There are also single S&F attachment mechanisms on

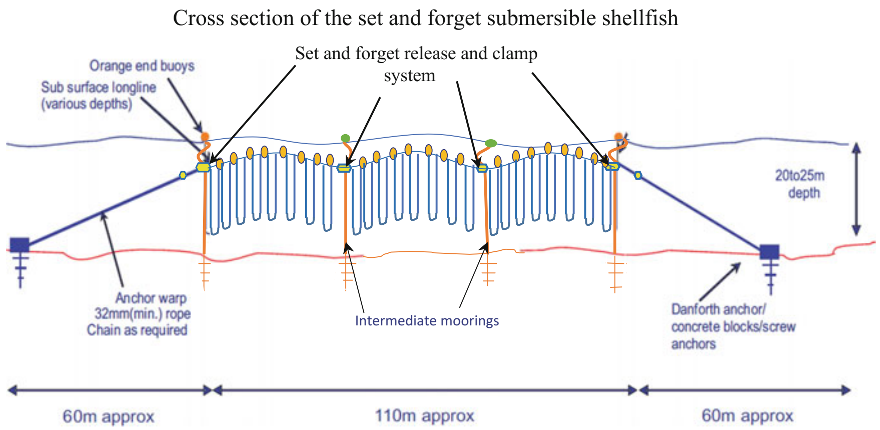

Fig. 3.3 Set and Forget system—next generation submersible backbone under testing (www.cawthron.org.nz)

each warp with a surface float. The idea is to fully seed the longline on the backbone. The backbone is then floated with sufficient buoys to support the intended harvest mass. Once seeded the backbone is pushed below the surface to the desired depth and the S&F mechanism engaged. The mechanisms on the warps are tightened to ensure the backbone does not collapse towards the center. The mussels can then be left until they are due to be harvested. No intermediate floatation is required. At harvest the mechanisms are released using a surface driven unit (physically not electronically) and the backbone rises to the surface to be harvested.

3.2.2 Oyster Farming in the Open Ocean

Oysters have also been tested on the open ocean sites. Although there are several methods used, inshore only bags have been tested in the offshore situation. Pacific oysters (*Crassostrea gigas*) have been held in purses or oyster bags (Fig. 3.4). The bags are configured one below the other in a “ladder” configuration. There are 20 bags in a ladder spaced approximately 50 cm (20 in.) apart with 50–100 oysters in each bag depending on bag size and oyster’s size. Some work is required in the design of the bags to reduce the maintenance of the present ladder system. Baffles have been introduced into the bags/purses to avoid the oysters being clumped into one corner of the unit. Oysters have to be at a minimum depth below the surface to avoid being “rumbled” by the wave energy which restricts shell growth. The level of floatation has to be managed to reduce excessive energy transfer to the culture units. Oysters have shown growth rates comparable with inshore waters in North Island. The Flat oyster *Tiostrea chilensis* will be tested in the same ladder system in

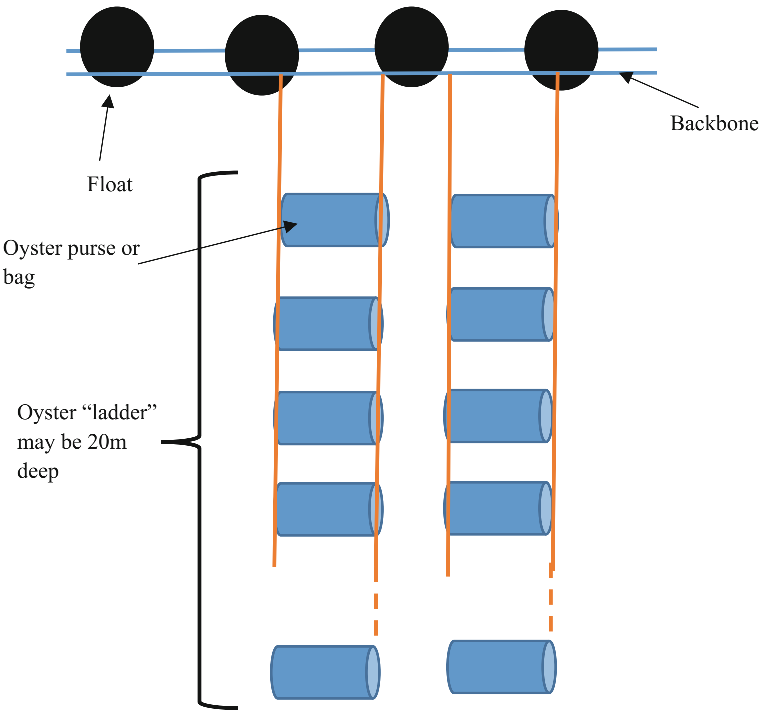

Fig. 3.4 Oyster purses being hung in a ladder configuration on the backbone

the near future on the open ocean farm. Early indicators are that flat oysters will grow in this system if they are away from direct wave energy.

3.3 Case Study on Submerged Aquaculture

3.3.1 Open Ocean Aquaculture in New Hampshire, USA

The University of New Hampshire (UNH) established the Open Ocean Aquaculture (OOA) research farm in 1999 (http://ooa.unh.edu/). The overall goal of the project was to stimulate the further development of commercial offshore aquaculture in New England. Also important was to work closely with commercial fishermen, coastal communities, private industry, and fellow marine research scientists to develop technologies for the aquaculture of native, cold-water finfish and shellfish species in exposed oceanic environments. The site was located 12 km offshore and in 52 m water depth, away from traditional fishing activities, recreational vessels and commercial traffic.

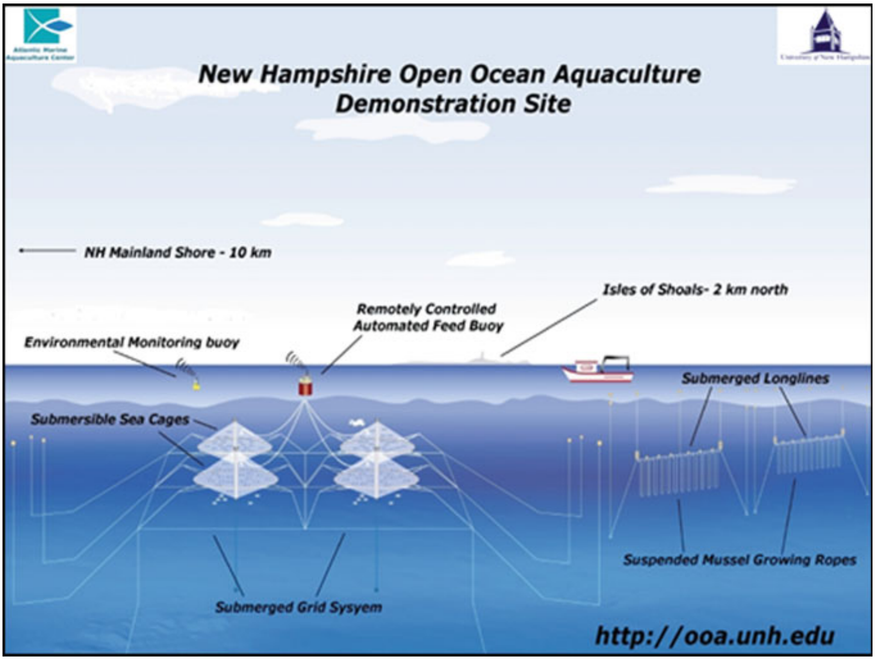

Fig. 3.5 Schematic of the University of New Hampshire Open Ocean Aquaculture site located 12 km offshore New Hampshire, USA

Prior to aquaculture systems going offshore, they were analyzed through numerical and physical scale modeling at the Jere Chase Ocean Engineering lab on campus. These tools help identify strengths and weaknesses of components, simulate failure scenarios and help determine safety factors before they deployed and field tested (Fredriksson et al. 2004; Swift et al. 1998; Tsukrov et al. 2000). The backbone of the OOA research farm was a 12 Ha, submerged grid for holding surface and sub-surface systems (Fig. 3.5). The four bay mooring had a scope of 3:1 and was held in place by 12, 1 ton embedment anchors (Fig. 3.6). The mooring complex was made from 5 cm dia. Polysteel lines that were tensioned and held in place by 1.43 m composite subsurface buoys in the corners and center of the grid (DeCew et al. 2010a, 2012; Fredriksson et al. 2004). The robust grid provided the necessary infrastructure to evaluate submersible cage systems (Chambers et al. 2011; DeCew et al. 2010b). One such system extensively tested was the Sea Station™ 600 and 3000 m^3 cages (Fig. 3.7a). Using a central spar with pennant weight, the cage could be submerged to a prescribed depth or lifted by compressed air to the surface. It utilized a Spectra net that shackled to the top and bottom of the central galvanized spar and used a middle ring that gave its bi-conical shape. Also evaluated offshore in the grid was a 600 m^3 geodesic Aquapod™ made with triangle panels and hard wire (Fig. 3.7b). This system was neutrally buoyant and be could set at various depths based upon the mooring configuration. Ocean Farm Technologies produces the

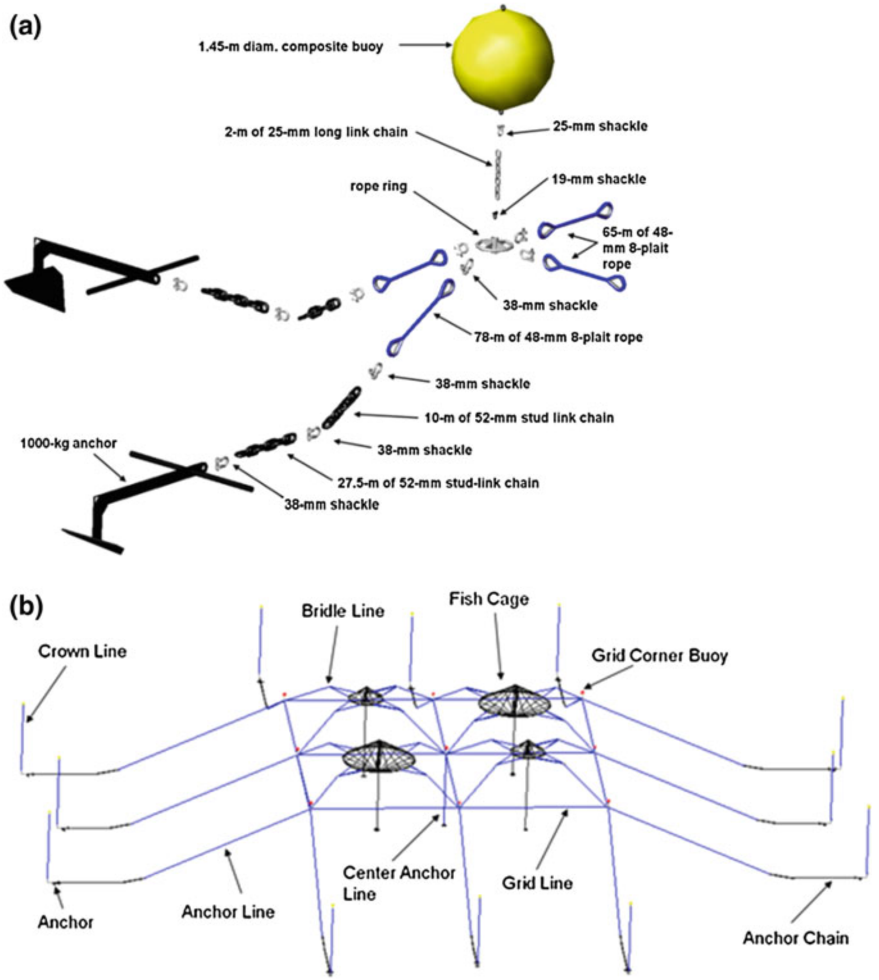

Fig. 3.6 Submerged grid mooring (**a**) and corner grid assembly (**b**). The side anchor assembly was similar except for the use of only one anchor leg and a 0.95 m steel float

Aquapod™ and since their initial sea trial in NH, have made many advances to their containment system. The American Soybean Association International Marketing (ASAIM) came forth with the Ocean Cage Aquaculture Technology (OCAT) system (Fig. 3.7c). The 100 m^3 cage OCAT (2 m × 4.5 m × 7 m) was constructed of HDPE pipe with galvanized steel fittings. Chain ballast hangs below the lower cage rim providing a restoring force. The net chamber is formed by attaching net panels to the cage framework. Engineers at UNH designed and evaluated components in the cage frame to make it a submersible system (DeCew et al. 2010b). Information gathered at the UNH OOA site helped these three companies improve their containment systems and increase global sales.

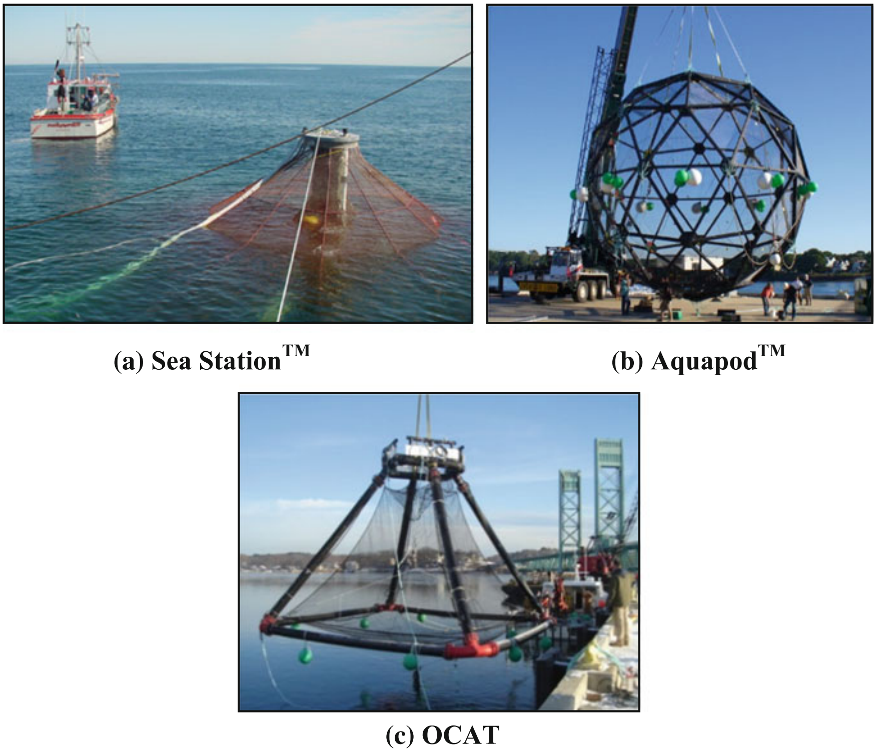

Fig. 3.7 Submersible cage systems (**a–c**) evaluated offshore New Hampshire. They include the Sea Station™, the Aquapod™ and the Ocean Cage Aquaculture Technology (OCAT)

Marine finfish species including summer flounder (*Paralichthys dentate*), cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), halibut (*Hippoglossus hippoglossus*), and steelhead trout (*Oncorhynchus mykiss*) were cultured and harvested from the research farm (Chambers and Howell 2006; Chambers et al. 2007; Howell and Chambers 2005; Rillahan et al. 2009, 2011). Hatchery production for cod, haddock and halibut was challenging with growout time in the sea cages ranging from 2.5 years (cod) to 3.5 years (halibut). Initially, fish were fed daily from a vessel through a feed hose that attached to the top of from the surface. An onboard water pump was used to mix food pellet and seawater in a funnel chamber before it was pushed down into a cage 12 m below. Autonomous feeders were not yet developed for the open ocean. Hence the design course that UNH Engineers embarked on to create three new generations of feeding systems (Rice et al. 2003). Prototype buoys evolved and scaling up to a final 20 ton version (Fullerton et al. 2004; Turmelle et al. 2006) that was fabricated by AEG in New Brunswick, CA (Fig. 3.8). The buoy hull was 8.6 $\times$ 6.9 m and had a draft of 3 m fully loaded with feed and fuel. To keep the buoy upright, 22,135 kg of concrete was poured into bottom. Fish food was pneumatically blown from a vessel into one of the four,

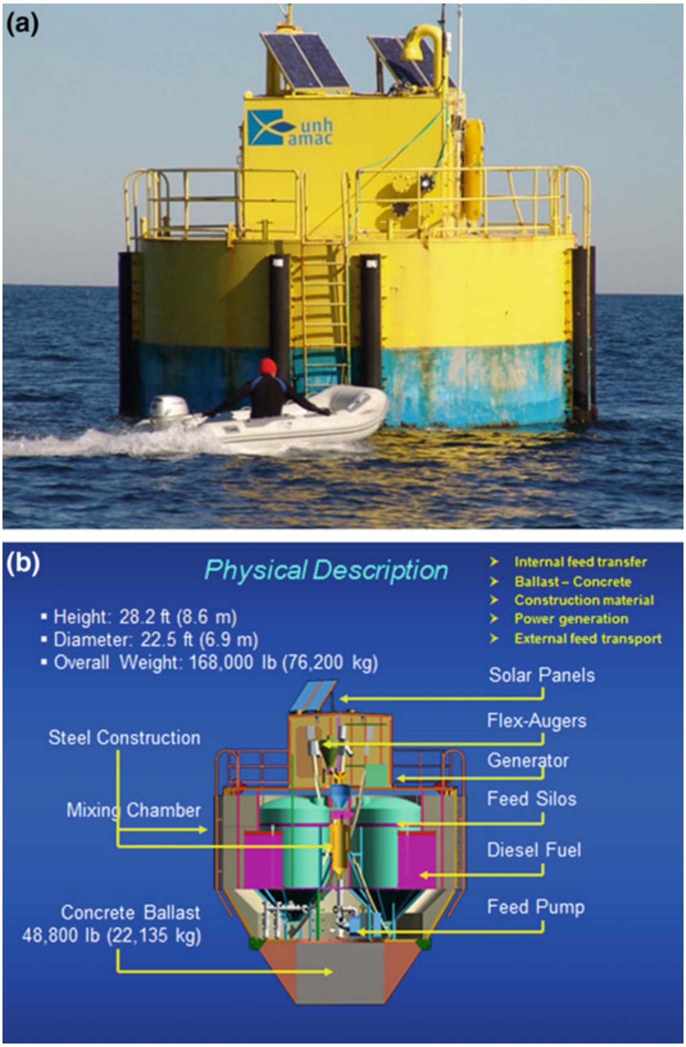

Fig. 3.8 Remote 20 ton feed buoy used to hydraulically feed four submersible sea cages up to 300 m away

5 ton silos. The house on top contained the majority of the electrical equipment as well as the generator for powering computers, pumps, valves, and augers used in daily feeding. During feed time, a flex auger would deliver feed pellets (5 mm) from the bottom of a silo to a mixing chamber in the top house. Feed rates were based upon fish species, size, biomass and temperature. In the mixing chamber, seawater was added before the feed was pumped hydraulically to individual cages. The buoy was moored adjacent to the cage grid by three, 750 ton Jeyco anchors. Feed distribution lines (4), consisting of 10 cm dia. High Density Polyethylene

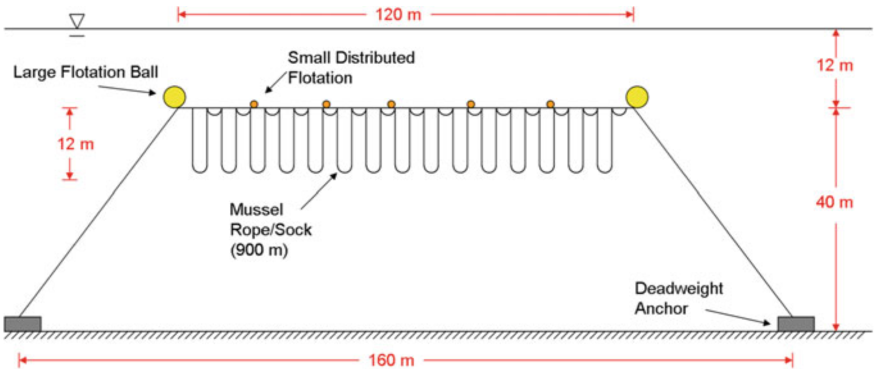

Fig. 3.9 Typical long-lines configuration for mussel grow-out. Dimensions are those used at the UNH OOA site and are representative

pipe, bolted to a manifold on the bottom of the buoy. They extended from the buoy to the submerged grid approximately 200 m away. Individual feed lines then integrated into the grid system and on to the top of each cage. Video cameras inside the cages were cabled through the feed lines back to the buoy.

Submerged shellfish longlines were designed and deployed next to the mooring grid (Figs. 3.5 and 3.9). Each 40 m long line was moored between two, 3000 kg dead weights (granite blocks) and set 12 m below surface to escape wave energies and predators (diving ducks). The backbone had surface lines so that it could be hauled up for seeding, cleaning or harvest. Approximately 900 m of mussel rope or sock could be deployed/line, able to produce between 8000 and 12,000 kg of blue mussel (*Edulis Mytilus*) per year (Langan and Horton 2003). The sea scallop (*Placopecten magellanicus*) was investigated on the submerged lines in stacked pearl nets. Problems with bio-fouling and stress from cleaning lead to low survival rates of this species.

Information important to scientists and farm managers was environmental conditions at the OOA site. This data was collected and streamed live from a single point, wave rider monitoring buoy (Irish et al. 2004, 2011). Figure 3.10 illustrates the instrumentation used at varying depths on the elastic buoy mooring. Oceanic parameters measured were wave height, current speed and direction (surface), temperature, salinity, oxygen, turbidity and fluorescence (at 1, 25 and 50 m depths).

Operations offshore were difficult to perform under winter conditions, heavy seas and with SCUBA divers. During the winter months, cages could not be accessed for several weeks at time thus minimizing days at sea for maintenance. Submerged cage systems were preferred in the North Atlantic to protect cage infrastructure and livestock. During Northeast storms, seas >10 m were recorded with currents speeds reaching 0.55 m/s. Underwater video cameras inside the cages provided insight to the fish health and feeding. This information was transmitted real time from the cages to the feed buoy and then back to shore through cellular modem.

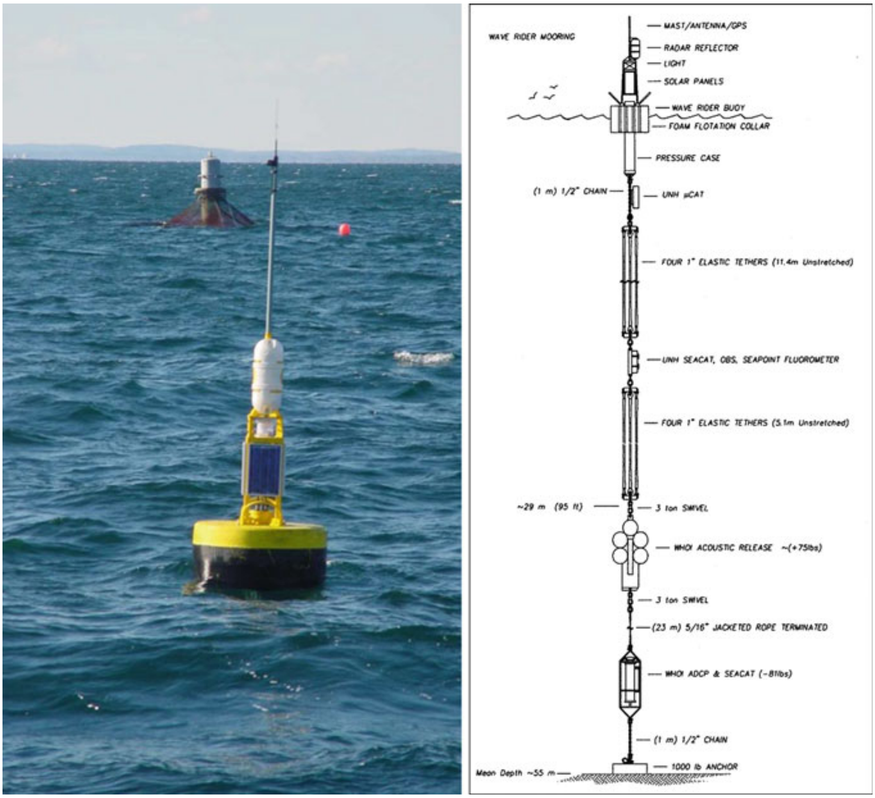

Fig. 3.10 Environmental monitoring buoy moored at the Open Ocean Aquaculture site. Oceanographic parameters measured included wave height, current speed and direction, temperature, salinity, oxygen, turbidity and fluorescence

Although the project succeeded in generating significant amounts of data and new information, the high maintenance costs, exposed nature of the site, and slow growth of marine fish species (cod, haddock and halibut) created operational and economic challenges.

3.4 Case Study on Multi-use on Open Ocean Environment

3.4.1 Methodology

This third case study picks up from the two previous case studies and details how the existing aquaculture technologies might be effectively utilized in a multi-use arrangement. In here, the multi-use of offshore wind energy and open ocean aquaculture is investigated experimentally. The location of interest for this feasibility study resides in the German bight at Veja Mate, which is reportedly 114 km off the shore in the North Sea. The reported results purely base on an experimental feasibility study since the stakeholder conflicts and the financial demand for in situ testing would have been too extreme at the point of development. The case study aimed to shed light on the general behavior of two different fish cage geometries being mounted to a tripile foundation for a 5 MW offshore wind energy converter (OWEC) at different submergence levels. An aspect of the analysis comprises the change of wave induced particle velocity and its distribution around the support structure due to the two fish cages. A second focus has been laid on the forces exposed to the tripile as a result of the additional fish cage bearing by means of force measurements under monochromatic waves. Thirdly the additional effects to potential scour around the tripile are also investigated in order to substantiate earlier findings (Goseberg et al. 2012).

The mechanical system of the fish cage and the OWEC-structure is investigated under regular wave attack with respect to (a) the deviations in the velocity field resulting from the fish cage underneath the OWEC, (b) the additional forces introduced by the fish cage and (c) the potential for scour evolution at the sea bottom of the OWEC location. Therefore a 110 m long and 2.2 m wide wave flume at the Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Hannover, Germany is applied. The experiments are scaled at Froude similitude at a length scale of 1:40. The water depth at the wave maker (piston type) equals 1.0 m, yet to investigate scour evolution at the OWEC-structure a 0.25 m deep sand pit (fine sands of $d_{50} = 0.148$ mm) is installed at a distance of 42 m of the wave maker. At the end of the wave flume a gravel slope acts as passive wave absorption. An overview of the wave flume, its installations and a schematic of the mechanic system under investigation is given in Fig. 3.11. The two fish cage models were made of solid brass. Variations with three different surface properties (net solidity) were accomplished under the attack of monochromatic waves.

Based on a potential building site in the German bight at Veja Mate, a frequent (mean) and an extreme wave with a 50-yearly reoccurrence interval have been chosen. In model scale investigated wave heights are $H = 0.04$ m with $T = 0.95$ s for the frequent case and $H = 0.28$ m with $T = 2.2$ s for the extreme wave condition respectively. Surface elevations are measured with capacity-type wave gauges at various positions. Deviations in the velocity field around the structure and the fish cage are recorded by either ADV probe inside the fish cage or by stereo PIV measurements around the fish cage. Wave-induced forces at the constructional conjunctions between fish cage and tripile legs are taken by force transducers measuring normal forces. Force measurements are designed to consequently separate horizontal and vertical forces. Therefore all conjunctions between the fish cage and the tripile legs are designed as pendulum rods whereas the vertical forces are assumed to be gathered by a single tension rod connected to the upper tripile intersection. Compression-tension type force transducers (HBM GmbH) with a capacity of 500 N and an accuracy of 2% of its capacity were used. Scour depth evolution was manually measured with sediment gauges of 2 mm PVC sticks which were observed by underwater cameras (Abus GmbH). This optical method

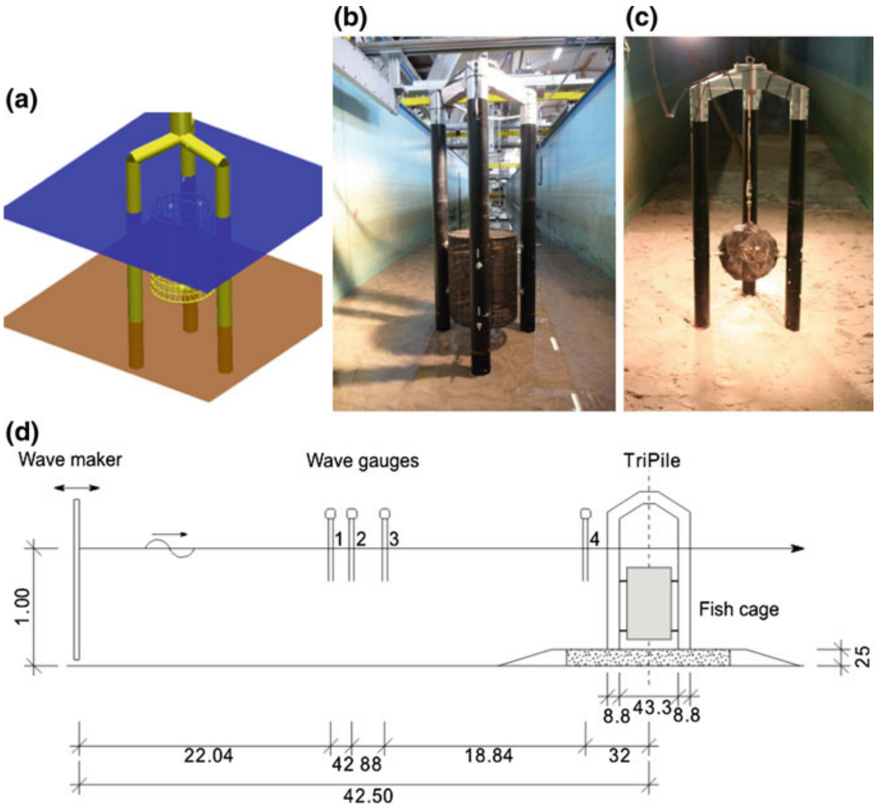

Fig. 3.11 **a** Schematic of the OWEC and cage arrangement. **b** Tripile model with cylindrical fish cage, **c** tripile model with spherical fish cage, and **d** longitudinal section of the wave flume with wave maker, position of wave gauges, sand pit and tripile model

where the difference between the initial and actual bed level is read from a centimeter scale on the PVC sticks based on the camera recordings gave reasonable accuracy (±0.5 cm).

3.4.2 Velocity, Force and Scour Regimes

Velocity measurements are accomplished to investigate the velocity regime in the vicinity of the OWEC-structure and its deviations by means of a fish cage installed inside the tripile legs. Foremostly, this part of the experimental program was intended to learn how velocities range inside the fish cage under wave attack in order to allow marine biologists to evaluate if fish production is feasible at all and how strong velocities influence the natural behavior of potential marine species

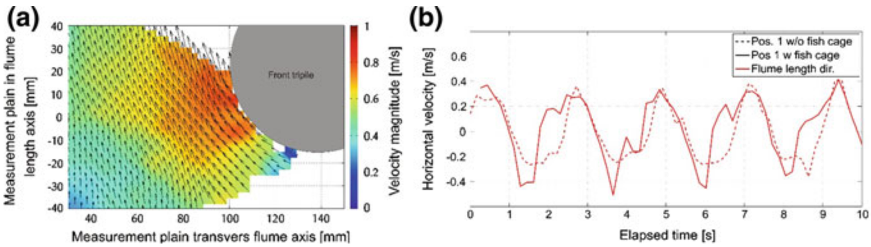

Fig. 3.12 **a** Example vector field of horizontal velocities near the front tripile for extreme wave conditions, upper measurement plain during wave crest propagation along the tripile. **b** Horizontal velocity from PIV-measurements comparing setup with and without fish cages assembled. All velocities reported are in laboratory scale. For prototype conditions multiply by $\sqrt{40}$

inside the enclosure. By means of the particle image velocimetry (PIV) technique (Raffel et al. 1998; Sveen and Cowen 2004) measurements of the velocity field very near to the tripile structure are feasible. Figure 3.12a shows an example of a velocity vector field during a propagation of a wave crest modeling extreme conditions for the cylindrical fish cage design.

Furthermore, the PIV-measurements which are recorded in stereo mode also allow for the extraction of 3D time series of velocities at a discrete position. For the evaluation of additional direct wave forces to the tripile legs the knowledge of velocity distribution is needed. Figure 3.12b hence shows the time series of horizontal velocities taken from PIV-measurements directly in front of the wave facing tripile leg at the height of the fish cage cover. Though maximum positive velocities are not significantly altered, it is obvious that negative velocities during wave trough are increased. Additionally it is apparent that phase duration of positive velocities is extended. With respect to fish cultivated in such a high energy environment a result could be that potential candidates have to be able to withstand such velocity magnitudes unharmed. Besides horizontal velocity components, vertical velocities are similar to their horizontal counterparts increased during the wave trough phase of wave passage. ADV-measurements inside the cylindrical fish cage reveal more moderate velocity changes which could be contributed to the damping effect of the modeled net material. While horizontal velocity deviations between experiments with and without fish cages are not so pronounced, it is apparent that vertical fluctuations are in a range of approx. 0.2 m/s (laboratory scale). This fact could especially influence health and behavior of flatfish which is one of the investigated candidates for the fish cages.

Force transducers in case of the cylindrical fish cage were arranged in two height levels. Force transducers FT_4 to FT_6 were mounted in the upper measurement plain connecting to the tripiles whereas the remainders (FT_1 to FT_3) were measuring forces near the bottom of the fish cages. Vertical forces were monitored with a single vertically arranged force transducer at the top cover of the cylinder. Compression forces were defined positive while tension forces were negative. Force transducers were pre-stressed and then zeroed before each experimental test for

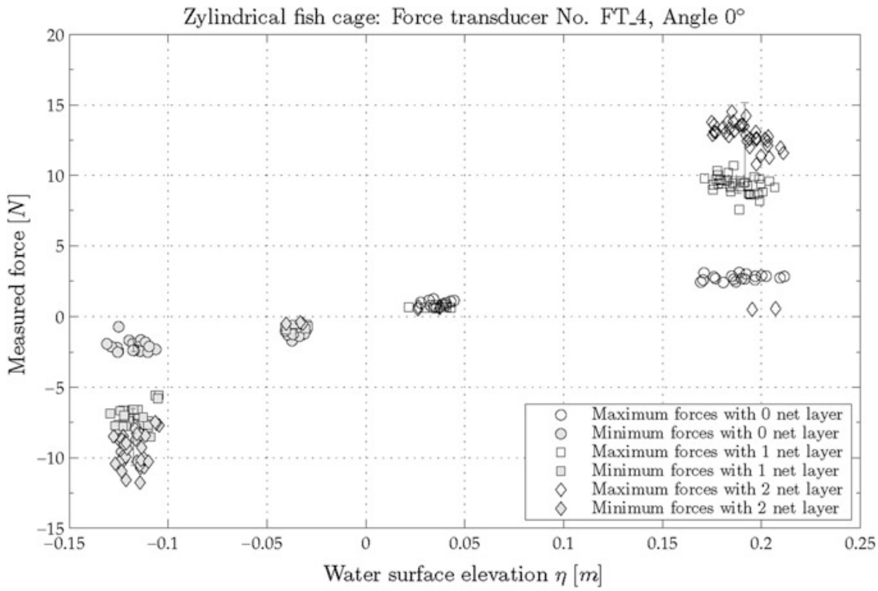

Fig. 3.13 Correlation of maximum wave heights and measured forces for cylindrical fish cages for force transducer FT_4 with respect to the number of net layers

stability reasons. Similarly, the spherical fish cage had three force transducers connecting from the equator of the sphere towards the tripiles plus a vertical force transducer to bear the vertical forces. Highest tension forces appear at the wave-facing tripile leg during the passage of the wave crest. In parallel, these forces initiated by the wave at the front of the cylinder are also measured at the backward force transducers but with opposite sign and vectorially separated.

In order to analyze the correlation between the wave heights and the caused reaction forces a zero-crossing method has been applied to the water surface elevation measurement which was located besides the wave-facing front tripile of the OWEC. Thereafter the maximum values of the surface elevation and the forces have been collected. Experimentally, three different flow resistances are considered. First, the fish cage is tested only with its support structure. One and two layers of net material are fixed to the fish cage in subsequent tests. Figure 3.13 shows an example of the correlation of maximum wave heights and the respective maximum force measured with respect to the number of net layers. In general it is apparent that the additional forces exerted to the tripile structure increase with increasing wave height. Though, the correlation is not linear but growth exponentially. Due to the limited number of wave heights analyzed so far it is yet not feasible to present valid regression functions. The influence of the flow resistance variation is though clearly obvious. While the increase of net layers from zero to one results in an increase of forces of more than 100%, the further increase towards two layers of net material only results in further loading of approx. 40%. The variation of let layer numbers is yet important to investigate how loadings develop under the additional resistance due to marine fouling. Up-scaled overall forces that have to be absorbed by the tripile structure are at least for stormy conditions in the mega newton range and deemed clearly design relevant for the OWEC structure. For the chosen cases, the connecting joints between the investigated fish cage variations are arranged so that bending moments are also induced. In upcoming studies it is thus recommended to lower the connecting joints further down to the sea bottom in order to greatly reduce the effects that aquaculture applications connected to the OWEC would have.

In literature a number of theoretical approaches exist to deduce the maximum scour depths at piles (Melville and Coleman 2000; Sumer and Fredsøe 2002) which nowadays depict an important piece of information for the safety assessment of OWEC. In case of complex marine constructions involving multi-use of an OWEC with multiple, complex-shaped constructional members, the analytical approaches are not easily applicable. Hence an optical method is applied which consists of sediment gauges and image capturing. A manual post-processing routine is chosen to estimate the local sea bed evolution. The local water depth of the modeled OWEC structure and the chosen monochromatic waves limit the scour tendency. Scour evolution is yet possible under the assumption that swell generated in a far field arrives at the location of interest. Therefore additional experiments with an elongated wave period of T = 3.0 s are conducted. In this case scour around the tripile legs can be observed clearly. Under the assumed boundary condition relative scour depth of S/D = 0.54 is determined at the front leg of the tripile whereas relative scour depth of S/D = 0.36 is found below the tower of the OWEC for a setup without a fish cage. Slightly different results are obtained under the presence of fish cages mounted to the OWEC. Relative scour depth of S/D = 0.48 (front leg) and S/D = 0.25 (central below tower of OWEC) are found. This reduction of scour observed underneath the main tower of the OWEC below the tower can be explained by a reduction of wave-induced flow velocities and shear stresses in this area.

3.5 Discussion and Conclusions

In the following, not only are conclusions drawn from the single case studies but it is highlighted how open ocean aquaculture might benefit from its transition towards a multi-use concept. Direct benefits such as cost reductions through multiple usage of anchor constructions as well as indirect ones like shared usage of supply vessels or personnel indicate that time has come to move aquaculture industry further offshore. Ongoing initiatives such as the European framework funded projects MERMAID, H2OCEAN, and TROPOS are a vital indication of the present demand for research and development in this area.

Open ocean shellfish farming is at a pivotal point at this time. Technology has reached a point where economically viable commercial production is a real prospect. Once production becomes more routine and operating under standard procedures, it is believed that companies will direct greater focus towards improving efficiency in a similar way the inshore longline system developed in New Zealand in the 80s and 90s. In further support of the open ocean mussel farm mentioned in the case study, mussel spat is being caught in commercial numbers as far as 12 km off the coast and may be accessible even further out to sea. This means the whole production chain can be handled on the same farm. It is estimated that this particular farm will deploy 350–400 km of mussel production rope per annum within the next 3–4 years. Once this farm has shown itself to be technically and economically viable, other farm owners have indicated that they will start production. The potential will then be enormous.

There are some considerations regarding production and seasonality that must be taken into account. It has been found that mussels inshore have a longer and more varied condition window than mussels grown offshore (Heasman, unpublished), i.e. shellfish conditioning at the open ocean site is more uniform across the growing area and is shorter in duration. This is an advantage in terms of processing however the shorter window leads to production peaks and troughs. For example, an offshore farm may be capable of producing 30,000 ton of mussels but if they all have to be harvested in a 6–12 week period it will require a large number of vessels and processing capability for that period. These units will sit idle or at low usage for the remainder of the year. For this reason it is important to have multiple species in production simultaneously, unless a species that can be harvested year round is utilized.

Despite the findings in New Hampshire, other open ocean locations and technologies may be more suitable for offshore farming. An example of this is Ocean Blue located 11 km offshore Panama. Here they are raising Cobia (*Rachycentron canadum*), a fast growing warm water species, in 6000 m^3 Sea Station™ cages. Last year they produced 400 MT with an expected 1200 MT by 2014. Currently they feed via day boats through pneumatic blowers into each cage. Commercial feed barges (http://www.akvagroup.com/products/cage-farming-aquaculture/feed-barges/ac-450-panorama) are available however they cannot withstand seas over 4.5 m. These barges are common in protected water ways in Norway, Chile and Canada. Certainly if aquaculture is to move further from shore, remote feeding systems will need to be improved to withstand seas >10 m. Also important will be real time monitoring of fish behavior and environmental parameters inside and outside the cages. In this, farmers can best manage animal welfare to optimize growth and condition.

Ocean farming will slowly creep offshore as new, economical and robust technologies develop. Farms of the future must be turnkey allowing for remote operations such as feeding, environmental monitoring, fish health and harvesting of product. These platforms could ultimately produce their own energy through wave, wind and tidal turbine technologies. Ultimately, farming centers should be located close to large coastal populations to reduce the carbon footprint from exporting overseas.

For the combination of aquaculture fish cages and OWEC structures, the up-scaled experimental particle velocities at the highest position of the investigated fish cages are in the range of 1.3 m/s under prototype condition for the maximum wave height (storm conditions). This range of velocities is potentially harmful to species candidates to be grown in the North Sea and might negatively affect survival rates and thus reduce economic feasibility of multi-use approaches. Alternatively, the investigated cage systems could be modified in height (decreased) and lowered further towards the sea bottom in order to circumvent the critical particle velocities induced by storm waves. However, volume reduction of the actual fish cages also minimizes the economic potential of the fish cages as the amount of fish is decreased.

This alternative design has similar potential to reduce overall forces at the contact points with the OWEC structure. In addition, as forces grow with the degree of marine growth, net materials with growth retarding characteristics in combination with optimized maintenance cycles might decrease overall forces as well. However, the greatest challenge for further testing in prototype conditions are still the restraints from owners or designers of offshore wind energy parks which reject any additional (and yet untested) loading stemming from secondary purposes for safety reasons. Unless legitimate doubts and technological uncertainties are alleviated through further scientific effort, it seems to date still challenging to expect marine multi-use applications in the near future.

In conclusion, based on differently far developed examples it has been demonstrated that open ocean aquaculture has reasonable potential for future growth and prosperity. In future, multi-use is not only a feasible add-on to farming in open ocean conditions whenever technological or logistical challenges are resolved thoroughly but it might depict the key innovation towards economically feasible offshore farming in high energy environments. For example, it might be beneficial for the aquaculture ventures to rely on pre-existing fixed structures such as piers, foundations amongst others to attach feeding storage, supply equipment or instruments. Rather than constructing and installation of dead weight anchors in rough environments, pre-existing infrastructure is seen advantageous to the installation of various forms of aquaculture technology including fish cages, mussel ropes or net pens. In turn, infrastructure owners would be able to generate additional income through leasing out their property to aquaculture.

However, some technological or logistical challenges which have been described can only be addressed efficiently with the help of stakeholder dialog and proper incorporation of end-users or operators. A chain of development steps from the very beginning of a business idea to the final operation of this business incorporates preliminary design, feasibility studies which involves various modelling steps, a design phase to plan for a prototype development, and eventually an operational farm or multi-use deployment which has undergone further optimization steps to yield its full effectiveness under a wide range of external influences. A number of approaches to tackle those steps of the development cycle have thus been highlighted in this paper aiming to help additional projects to be launched in the future.

References

Buck, B. H., & Buchholz, C. M. (2004). The offshore-ring: A new system design for the open ocean aquaculture of macroalgae. *Journal of Applied Phycology, 16,* 355–368.

Buck, B. H., & Buchholz, C. M. (2005). Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. *Aquaculture, 250,* 674–691.

Chambers, M. D., DeCew, J., Celikkol, B., Yigit, M., & Cremer, M. C. (2011). Small-scale, submersible fish cages suitable for developing economies. *Global Aquaculture Advocate, 14,* 30–32.

Chambers, M. D., & Howell, W. H. (2006). Preliminary information on cod and haddock production in submerged cages off the coast of New Hampshire, USA. *ICES Journal of Marine Science*, *63*(2)

Chambers, M. D., Langan, R., Howell, W., Celikkol, B., Watson, B., Barnaby, R., et al. (2007). Recent developments at the University of New Hampshire Open Ocean Aquaculture Site. *Bulletin-Aquaculture Association of Canada*, *105*(3).

DeCew, J., Baldwin, K., Celikkol, B., Chambers, M., Frederiksson, D. W., Irish, J., et al. (2010a). Assessment of a submerged grid mooring in the Gulf of Maine. In *OCEANS 2010*. doi:10.1109/OCEANS.2010.5664025

DeCew, J., Celikkol, B., Baldwin, K., Chambers, M., Irish, J., Robinson, M. R., et al. (2012). Assessment of a mooring system for finfish aquaculture. *Journal of the World Aquaculture Society*, *43*, 32–36.

DeCew, J., Frederiksson, D. W., Bugrov, L., Swift, M. R., Eroshkin, O., & Celikkol, B. (2005). A case study of a modified gravity type cage and mooring system using numerical and physical models. *IEEE Journal of Oceanic Engineering, 30,* 47–58.

DeCew, J., Tsukrov, I., Risso, A., Swift, M. R., & Celikkol, B. (2010b). Modeling of dynamic behavior of a single-point moored submersible fish cage under currents. *Aquacultural Engineering, 43,* 38–45.

Drumm, A. (2010). *Evaluation of the promotion of offshore aquaculture through a technology platform (OATP)* (p. 46). Galway, Ireland, Marine Institute. Retrieved October 1, 2016, from www.offshoreaqua.com/docs/OATP_Final_Publishable_report.pdf

FAO. (2012). *FAO yearbook. Fishery and Aquaculture Statistics 2010*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Fredriksson, D. W., Swift, M. R., Eroshkin, O., Tsukurov, I., Irish, J. D., & Celikkol, B. (2004). The design and analysis of a four-cage, grid mooring for open ocean aquaculture. *Aqua Engineering, 32,* 77–94.

Fullerton, B., Swift, M. R., Boduch, S., Eroshkin, O., & Rice, G. (2004). Design and analysis of an automated feed buoy for submerged cages. *Aquacultural Engineering, 95,* 95–111.

Goseberg, N., Franz, B., & Schlurmann, T. (2012). The potential co-use of aquaculture and offshore wind energy structures. In *Proceedings of the 6th Chinese-German joint symposium on hydraulic and ocean engineering (JOINT 2012)*. Keelung, Taiwan: National Taiwan Ocean University.

Hau, E., & von Renouard, H. (2006). *Wind turbines: Fundamentals, technologies, application, economics*. Heidelberg/Berlin, Germany: Springer.

Howell, W. H., & Chambers, M. D. (2005). Growth performance and survival of Atlantic halibut (*Hippoglossus hippoglossus*) grown in submerged net pens. *Bulletin-Aquaculture Association of Canada, 9,* 35–37.

Huang, C.-C., Tang, H.-J., & Liu, J.-Y. (2006). Dynamical analysis of net cage structures for marine aquaculture: Numerical simulation and model testing. *Aquacultural Engineering, 35,* 258–270.

Huang, C.-C., Tang, H.-J., & Liu, J.-Y. (2008). Effects of waves and currents on gravity-type cages in the open sea. *Aquacultural Engineering, 38,* 105–116.

Irish, J. D., Carrol, M., Singer, R. C., Newhall, A. E., Paul, W., Johnson, C., et al. (2011). *Instrumentation for open ocean aquaculture monitoring*. WHOI. doi:10.1575/1912/25

Irish, J. D., Fredriksson, D. W., & Boduch, S. (2004). Environmental monitoring buoy and mooring with telemetry. *Sea Technology, 45,* 14–19.

Kapetsky, J. M., Aguilar-Manjarrez, J., & Jenness, J. (2013). A global assessment of potential for offshore mariculture development from a spatial perspective. FAO Fisheries and Aquaculture Technical Paper 549. Rome, Italy: Food and Agriculture Organization of the United Nations.

Lacroix, D., & Pioch, S. (2011). The multi-use in wind farm projects: More conflicts or a win-win opportunity? *Aquatic Living Resources, 24,* 129–135.

Lader, P. F., & Enerhaug, B. (2005). Experimental investigation of forces and geometry of a net cage in uniform flow. *IEEE Journal of Oceanic Engineering, 30,* 79–84.

Langan, R., & Horton, C. F. (2003). Design, operation and economics of submerged longline mussel culture in the open ocean. *Bulletin of the Aquaculture Association of Canada, 103,* 11–20.

Langhamer, O., & Wilhelmsson, D. (2009). Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes—A field experiment. *Marine Environmental Research, 68,* 151–157.

Liu, T.-L., & Su, D.-T. (2013). Numerical analysis of the influence of reef arrangements on artificial reef flow fields. *Ocean Engineering, 74,* 81–89.

Marra, J. (2005). When will we tame the oceans? *Nature*, *436*. doi:10.1038/436175a

Melville, B. W., & Coleman, S. E. (2000). *Bridge scour*. Littleton, Colorado: Water Resources Publications.

Raffel, M., Willert, C., & Kompenhans, J. (1998). *Particle image velocimetry—A practical guide*. Berlin/Heidelberg, Germany: Springer.

Rice, G., Stommel, M., Chambers, M. D., & Eroshkin, O. (2003). The design, construction, and testing of the university of New Hampshire feed buoy. Open Ocean Aquaculture, From Research to Commercial Reality, The World Aquaculture Society

Rillahan, C., Chambers, M., Howell, W. H., & Watson, W. H. (2009). A self-contained system for observing and quantifying the behavior of Atlantic cod, *Gadus morhua*, in an offshore aquaculture cage. *Aquaculture, 293,* 49–56.

Rillahan, C., Chambers, M. D., Howell, W. H., & Watson, W. H. (2011). The behavior of cod (*Gadus morhua*) in an offshore aquaculture net pen. *Aquaculture, 310,* 361–368.

Sumer, B. M., & Fredsøe, J. (2002). *The mechanics of scour*. Singapore: The Marine Environment, World Scientific.

Sveen, J. K., & Cowen, E. A. (2004). *PIV and Water Waves, Kapitel: Quantitative imaging techniques and their application to wavy flow*. Singapore: World Scientific.

Swift, M. R., Palczynski, M., Ketler, K., Michelin, D., & Celikkol, B. (1998). Fish cage physical modeling for software development and design applications. In Proceedings of the 26th U.S.-Japan aquaculture symposium nutrition and technical development of aquaculture (pp. 199–206), University of New Hampshire, Durham, NH.

Tsukrov, I., Eroshkin, O., Frederiksson, D., Swift, M. R., & Celikkol, B. (2003). Finite element modeling of net panels using a consistent net element. *Ocean Engineering, 30,* 251–270.

Tsukrov, I., Ozbay, M., Swift, M. R., Celikkol, B., Fredriksson, D. W., & Baldwin, K. (2000). Open ocean aquaculture engineering: Numerical modeling. *Marine Technology Society Journal, 34*(1), 29–40.

Turmelle, C., Swift, M., Celikkol, B., Chambers, M., DeCew, J., Fredriksson, D., et al. (2006). Design of a 20-ton Finfish Aquaculture feeding buoy. *Proc. Oceans06*. Boston, MA.

Table 11.6 Site-specific data of the offshore wind farm-aquaculture multi-use concept at the offshore lighthouse "Roter Sand" (modified after Buck et al. 2010, based on Buck 2004 and Buck et al. 2008a, b)

Basic data	
Distance to shore (City of Bremerhaven)	17 nautical miles
Number of planned wind turbines/power	18/5 MW-class
Salinity	20–33‰ (due to tidal current and the influence of the Weser estuary)
Depth	10–15 m
Condition of the sea bottom	Soft bottom (Wadden Sea)
Turbidity and light	High sediment load (due to the Wadden Sea)
Wave climate	exposed
Current velocity	0–1.2 m s^{-1} (depending on the tide)
Significant wave heights	0–6 m
Nutrients	Eutrophic situation
Water temperature	1.5–18 °C
Wind velocities	Up to 8 Beaufort
Distance between turbines	Approx. 1,000 m
Minimum spacing between turbines and any aquaculture co-use	150 m
Size of aquacultural area (single mussel plot)	700 × 700 m (490,000 m^2 = 0.49 km^2 = 49 ha = 121 acre)
Number of single mussel plots	4 (196 ha = 484 acre)
Total length of the collector harness per longline	1675 m (335 V-shaped collector pairs having each a length of 2 · 2.5 m = 5 m, 71 · 1675 m = 118,925 m per single mussel plot
Biomass of mussels per meter of collector	10–15 kg (16.75 metric tons · longline^{-1}, 1190 metric tons · plot^{-1})

11.6.2 Data for the Economic Analysis

(1) See Table 11.6

(2) As the best and safest working conditions are to maximize onshore activities (Sørensen et al. 2001), the setup of all longline devices should take place on land-based facilities and transferred to the aquaculture site during spring to allow settlement in May of the same year. It was planned to install two full mussel plots, which were scaled up in the following year, which would then be equivalent to four mussel plots in operation. Exchange of longline devices after its operating life expectancy can automatically be done during or after maintenance or harvest procedures. Consumption mussels reach market size after approximately 1.5 years; therefore, the farm will operate at full scale in the second year, which results in a form of shifting cultivation (Bartlett 1956). While only in the first year of the enterprise no mussels can be harvested due to their growth period to reach market size, in the following years two plots can be

harvested biennially each year (6 harvests in four years). Once the longline is transferred at sea, deployed and ready for cultivation the production undergoes two cycles: Spat collection (April–June) in year one and maintenance of longlines to remove fouling organisms and modify buoyancy (August–May) in year one as well and grow-out to consumption size within 15–18 months (market size: <5.5 cm) and harvest in August–November in the second year.

(3) All costs were itemized by scenarios of production for consumption mussels (Buck et al. 2010 also calculate seed mussel production). Cost calculations were based on data gathered from existing traditional nearshore mussel cultivation activities. Some nearshore cultivation plots have a distance of 10–55 nautical miles to the port of trans-shipment, which is within the scale of the planned offshore site (17 nautical miles) (BSH 2016). Offshore operations are more labour and time intensive than nearshore sites. Much of the labour is for maintenance that includes deploying or retrieving of moorings or other parts of the construction harness, which may lead to generally higher operation and production costs. However, some production steps necessary for nearshore operations cease to exist offshore, which in turn leads to cost reduction. The annual fixed costs consist of depreciation, licenses, motor overhaul, interest on fixed capital and miscellaneous costs like insurance premium and administrative cost. Interest rate was assumed to be 7%. Variable costs are fuel expenses, wages, repairs and maintenance, miscellaneous costs and interest on variable costs. Fuel was assumed to cost 0.55 € liter^{-1}, wages are calculated with 3,333 € month^{-1}. When using existing capacities of mussel farming in Lower Saxony, an investment for retrofitting at the beginning of the enterprise will be required. In the scenarios where new capacities have to be established, investment into a new appropriate vessel as well as into a new land facility was considered. All other costs are assumed to be similar to those used for the basic scenario.

(4) A sensitivity analysis was calculated to explore the effects of changes in the key parameters that reflect uncertainty, such as the biomass gain and/or the development of costs and prices. Here, NPV and IRR for different mussel prices, different biomass gain, different developments of single cost components as well as an increase in overall costs were calculated as well as different discount rates on NPV.

11.6.3 Calculation and Results

Following the data of the Federal Agency for Agriculture and Food (2007) and the State Fisheries Agency, Bremerhaven, Germany (SFA) (2008), the average market price per kg of consumer mussels has been relatively stable until 1975 (below 0.2 € kg^{-1}). Afterwards, the price has been subject to fluctuations ranging between

0.50 and 1.96 € kg^{-1}. According to the development of the market price of Blue mussels, a price of 1.0 € kg^{-1} of mussels was used in the base scenario (SFA 2008). Thus, a single longline could have a production value of 16,750 € (1,000 € × 16.75 metric tons) and a single mussel plot of approx. 1,190,000 € (1,000 € × 1190 metric tons).

The cost of longlines including the complete harness is the sum of various individual costs and levels around 15.80 € $meter^{-1}$ of longline (including collectors, mooring constructions, connecting pieces for the entire longline device, such as shackles, swivels, rings as well as the complete buoyancy). Costs were calculated by Sahr (2006) using the equations for the definition of key cost data published in Pelz (1974). This leads to an overall investment cost of approximately 835,500 € single mussel $plot^{-1}$ every four years. In line with the estimates of Whitmarsh et al. (2006) the operating life expectancy is assumed to be four years for longlines and collectors, six years for buoyancy, and 10 years for anchors. A vessel adapted for performing offshore operations is needed. In the base scenario, an investment in a new vessel (45 m class, 430 GRT, 500 kW) for around 4 million € (Sahr 2006), including all necessary equipment for longline cultivation, was assumed. This case also includes a complete motor overhaul after 10 years with 385,000 € (assuming motor costs to be 17.5% of total vessel investment and retrofitting to be 55% of the amount of 17.5%; Sahr 2006). Because the mussel farmer community already disposes of mussel farming cutters used for bottom culture, we also calculated the NPV with the assumption of using existing capacities of mussel farmers. Investment will then be reduced to the retrofitting of the vessel only, which was calculated with costs of about 750,000 € (Sahr 2006). Capital investment costs include the costs of a land facility for the purpose of equipment storage and for carrying out land-based activities, such as tying and repairing collectors and other equipment. Investment costs for a land facility are assumed to be 1,500,000 €. Licensing costs for a single mussel plot at the offshore site Nordergründe is based upon the scale of charges and fees of the State of Lower Saxony (NKüFischO 2006). Following the fees for mussel license areas, only the bureaucratic work load will be charged, which was calculated by the *State Fisheries Agency* (SFA*)* in Bremerhaven with a nonrecurring charge of approximately 1,000 € (personal communication with Brandt from SFA). Miscellaneous fixed costs (e.g., insurance premiums) are assumed to be 5% of depreciation leading to a total sum of 151,127 € in four years. Interest on fixed capital is 232,951 € for a four-year period. Total fixed costs were 3,560,817 €.

11.6.3.1 Operation Costs

The experience of the bottom-culture aquaculturists indicates that approximately 70 days per year are needed for labour at four culture plots, amounting altogether to 280 offshore working days in four years. Taking into account 61.8% of full load engine performance in a 24 h day, fuel costs per day at sea are estimated to be 1200 € (Gloy 2006; Sahr 2006). This totals 84,000 € per year or 336,000 € in four years. Two full positions and two seasonal employees are required per year. The latter are employed only in times of the heaviest workload in the 6 months from spring to autumn. Labour costs total 479,952 € in a four-year period. Costs of maintenance and repairs, estimated as 10% of the yearly depreciation, are 302,254 €. Miscellaneous variable costs are estimated to be 5% of depreciation, total 151,127 € in four years. Interest on operating capital sums to 88,853 € in four years. Total variable costs were 1,358,186 €.

11.6.3.2 Enterprise Budget Analysis

Costs and receipts of two case-scenarios were calculated for consumption mussels. Scenario 1: Production of consumption mussels with Investment into a new vessel. This is the base scenario assuming a four million € investment into a new vessel for farming of mussels for consumption. A general overhaul of the motor is necessary after 10 years and is calculated with 385,000 €. Net returns for an average four year period sum to 4,594,996 €. Scenario 2: Production of consumption mussels using free capacities of existing mussel farmers. For this scenario, retrofitting costs for the vessel are about 750,000 €. No land-based facility is included. This leads to net returns of approximately 6,022,000 € in four years, which is 1.3 times higher than in the base scenario.

11.6.3.3 Productivity Measures

Break-even yield and break-even price were calculated to estimate the minimum level of biomass production and the minimum price per kg mussel to enable the enterprise to cover cost. Assuming a biomass of 10 kg meter^{-1} (consumer mussels) the break-even price is 0.52 € when a new vessel and land facility is taken into calculation. Using existing equipment, a break-even price of 0.37 € results. In the case of seed mussels the break-even price varies between 0.34 and 0.49 €. Break-even yield for the consumer mussel scenarios lies between 3.67 kg and 5.17 kg per meter longline, respectively, assuming a mussel price of 1 € kg^{-1}. In the seed mussel scenario the break-even yields range from 3.42 to 4.92 kg. Actual prices and yields observed at field experiments are higher than the break-even values. This indicates the profitability of both practices, while the consumer mussel production is clearly more above those criterions for economic viability.

11.6.3.4 Investment Appraisal

Assuming the operating life expectancy of a new vessel to be 20 years, we calculate the NPV of cash flows over 20 years with a discount rate of 7% in the basic model. This rate is chosen according to Liu and Sumaila (2007), who argue that the most frequently used discount rate by Nature Resources Canada is within a range of

5–10%. D’Souza et al. (2004) used 7, 9 and 11%, while Whitmarsh et al. (2006) limits the discount rate to 8%. Due to the sensitivity of the NPV to the discount rate, values ranging from 6 to 9% were used. In the base scenario, the price for one kg of mussels was assumed to be 1.0 €. Net present value amounts to 5,667,073 €, with an IRR of 14.73%. When using existing capacities of mussel farming in Lower Saxony, an investment of about 750,000 € for retrofitting of the vessel at the beginning of the enterprise will be required. All other costs are assumed to be similar to those from the basic scenario. NPV levels around 9,622,937 € and an IRR of 28.11%. Economically, the most promising enterprise is the production of consumer mussels if existing equipment can be used. But also in the case of a new vessel and a new land facility profits are likely, since the IRR levels at 14.73%. This should be in most cases higher than the costs of capital.

11.6.3.5 Sensitivity Analysis

A sensitivity analysis was carried out to assess the economic feasibility, if key parameters of the economic analysis are changing. As the biomass harvested was assumed to be at a low level, the positive impact of a 25 and 50% biomass increase was estimated for consumer mussels as well as an increase of 10% for seed mussel yield. Fuel costs were increased by 10 and 20% per year, wages by 3% per year, longline costs by 5% per year and total costs by 5% per year. Discount rates were varied from 5% over 6 to 8%. The mussel price was changed by 10% in case of consumer mussels and by 20% in case of seed mussels. The results are shown in Table 8. The overall result shows the capacity of the production of consumer mussels with existing equipment to withstand cost increases quite well. In case of a new vessel and new land facility NPV remains positive except for an overall cost increase of 5% per year. All calculated discount rates leave NPV to be positive.

11.6.4 Final Conclusion

Assuming a baseline production of 2380 tons of consumption mussels per year (2 plots) the results of the economic study show that the base scenario is clearly beyond the break-even point. Varying parameter values, such as investment costs concerning longlines, new vessels or retrofitting, operating costs like wages and fuel, biomass yield, market price, total cost increases, and different discount rates, show different levels of feasibility. Offshore mussel production for consumption is profitable, but profits are less with a new vessel and a new land facility and higher in the scenarios without a new vessel and a new land facility, respectively. The NPV and IRR are large enough that this business can be recommended as long as there are existing capacities. Of course, all businesses can become profitable and respectively more profitable if costs can be reduced and revenues increased.

The lack of practical experience of culturing mussels in exposed environments precludes estimating effects of economic risks.

11.7 Ownership Issues

11.7.1 Modes of Cooperation

The relevant government policy as a central framing condition must be part of any analysis of likely management scenarios for an integrated wind energy-mariculture facility. In the North Sea area, the here presented concept is ahead of the current institutionalized regulatory system. Indeed, a systematic regulation addressing this multi-use concept in the context of industry support is yet lacking. While current legislation may preclude concurrent economic activity within offshore wind farms, that likely can be interpreted as a de facto law absent any regulatory consideration on this multi-use issue. However, given the strong push for spatial efficiency and multi-use concepts in the maritime waters in the EU and elsewhere (Krause et al. 2003; Lutges and Holzfuss 2006), it can be expected that more comprehensive regulatory frameworks will develop in due time. Krause et al. (2011) identified three likely avenues under which an integrated mariculture-wind energy facility may be organized. These are not exhaustive, or mutually exclusive from each other, but rather provide a straightforward method for categorizing potential outcomes. In the following, a brief synopsis of these three different ownership scenarios of multi-use in the offshore realm is provided.

11.7.1.1 Sole Owner

At the extreme end, a sole owner situation could be envisaged, in which a multiple use business plan could be enacted by a sole company without any cooperation. This set-up may accommodate especially the interests of the wind energy producers, who would have easier access to the financial resources needed. In view of the current complexity of drafting and following a contract with an outside firm makes this sole owner approach highly appealing. Indeed, from an economic point of view, governance structures that have better transaction cost economizing properties are preferable. Additionally, transaction cost economics suggests that full vertical integration completely resolves issues related to hold-ups and misaligned incentives (Williamson 1979, 1981; Johnson and Houston 2000).

Undeniably, the potential for further net revenue via mariculture may be alluring to a wind energy firm, especially in the light that the area occupied by wind turbines is roughly 1–3% of the total area of an offshore wind farm (Mee 2006). Economies of scope may act thus as a financial catalyst, i.e. simultaneously producing two products with a lower average cost than if undertaken separately.

Undertaking this economic decision as a sole firm partly however rests on the ability of the wind energy producer to culture products at a similar or lower average cost than if they had negotiated a contract or formed a joint venture with a firm who specializes in mariculture. The lack of knowledge on the different modes of conduct in the mariculture section could act however, as a major impediment to such sole ownership scenario of a wind farm enterprise. Thus, while a sole ownership approach may initially appear promising, the degree of risk involved in operating two very different businesses at the same location is high. The relative risk of internalizing both productive activities can be somewhat combatted by the degree to which personnel with specialized knowledge could be brought into oversee and conduct these operations. Current lines of research are assessing the economic merits of a joint mariculture-wind energy facility and will help illuminate the viability of such a venture from multiple perspectives (Griffin and Krause 2010).

11.7.1.2 Negotiated Contract

Forming alliances is a common commercial strategy that is employed to organize and mitigate activities that are riskier than a firm's average inside project. These alliances occur more in riskier industries (Robinson 2008). Expanding to an industry-level analysis, Robinson (2008) found that alliance intensity across industries is positively associated with the risk difference between the two industries. This dynamic could play an important role in alliance formation versus single firm management of a multi-use facility. Therefore negotiated contracts are a alternative path to mitigate and manage the risk associated to an integrated facility. Such categories of agreement may cover a multitude of different settings, such as a joint venture or a consortium or any form of subcontracts. Central hereby is the fact that the outlined interdependence between firms must provide benefit to each party (Pareto-improving) and be perceived as fair by the participating entities. Continued cooperation between parties must be sustainable by the underlying game structure (Grandori and Soda 1995). Alliance between firms that both hold unique capabilities that neither partner could efficiently provide alone, have the highest potential for coordination. Michler-Cieluch and Krause (2008) showed that under such an umbrella there is sufficient scope for such wind farm-mariculture cooperation in terms of operation and maintenance activities.

However, the process of drawing up a contract that delineates the lines of cooperation between firms is fraught with challenges. Hold-up hazards increase when complexity and uncertainty make writing and enforcing contracts difficult (Williamson 1979), and when products require asset-specific investments, two conditions that hold in this case. Only when there are offsetting economic benefits and sufficient efficiency scope to doing so firms are compelled to engage in integrated organisational structures over simple contracts or sole ownership (Johnson and Houston 2000). Such economic benefits pertain to any of the previously outlined benefits from cooperation, such as reduced production costs, organisational efficiencies, or pooling risk—but these benefits are not guaranteed. Because of the parties' inability to write an a priori comprehensive agreement that covers all future contingencies, Nielsen (2010) argued that all alliance contracts are necessarily incomplete. Thus, these contracts may enhance or prohibit desired outcomes. In order to be successful, all stakeholders involved in such joint cooperation agreements must be informed and clear about their expectations, rights and duties involved from the onset if being engaged in such multiple use setting.

Regarding the predictors of success in joint ventures and other alliances, an amount of considerable research exists. Johnson and Houston (2000) find that only joint ventures between firms in related businesses are likely to generate operating synergies. Thus, combinations of dissimilar firms can reduce value by contributing to bureaucracy and lack-of-focus. Beamish (1994) finds that the good intentions and rational motives behind alliances are often not congruent with the strategic direction of either firm on its own. This inconsistency can lead to poor performance and instability. Indeed, Kumar (2007) finds that in incidences where firms with asymmetric resource endowments enter into a joint venture, asymmetric wealth gains arise via the negative wealth transfer effects of resource appropriation by the firm with more valuable resources. Therefore, initial collaborative research between sectors prior to the design and execution of a commercial agreement by act as avenue to overcome this potential pitfall Michler-Cieluch et al. (2009a). In the German case study, our interviews and survey work suggests that the stakeholders in a potential mariculture-wind energy facility may be amenable to some type of contracted agreement. Respondents have suggested that they would be open to the idea of contracting out culturing activities at the site of an offshore wind farm as a prior joint research initiative and feasibility study. It does seem unlikely though at this point that a contracted solution could occur in the absence of some intervening third body (Michler-Cieluch et al. 2009a). However, an advisory or some other external independent mediating group or entity that helps to coordinate and facilitate the entire process generally improves the chances of reaching a successful agreement (Noble 2000).

11.7.1.3 Legislated

In the third ownership option, a legislative prescription could attain desired policy goals of spatial efficiency in the ocean area. The use of mandates, subsidies, tariffs, and other policy tools can change the incentives of the current economic environment to make the multi-use concept economically viable in cases where it may not be to date very appealing or in places where finding a direct commercial market solution for multi-use in the offshore setting is not possible. Increasingly, policy makers may find policy instruments as a palatable solution for achieving policy goals, especially as there is a growing focus on coastal zone management and the efficient and equitable use of coastal resources in the EU, US, and elsewhere (Krause et al. 2003, Lutges and Holzfuss 2006; Rhode Island Coastal Resources Management Council 2010). Mariculture can offer expanded employment opportunities to rural peripheral regions and displaced fishermen in the area of a wind energy facility. Furthermore, it has the potential to make wild harvest fisheries more productive if mariculture areas act as nurseries for wild fish (Mee 2006). Indeed, multi-use layering of economic activities can maximize the value of offshore resources while reducing conflict between stakeholder groups. Since regulators have already shown they are comfortable with using legislation to spur growth in the offshore wind energy industry, such type of legislative promoting a multi-use concept would not be an uncommon step. Indeed, a clear, coherent, and stable regulatory framework is a bare minimum when firms make financial decisions in the inherently risky offshore marine environment. Managers need to be able to predict with some certainty the expected outcomes of changes in strategy, be it an internal decision or the decision to form an external alliance. To the contrary, fragmentation in the structure of State decision making is shown to lead to more elaborate and costly inter-organisational networks (Carroll et al. 1988). However, the decision to actively foster cooperation on a multi-use concept should largely be dependent on market conditions, which must be somewhat accommodated for by the legislation. The latter may be driven by the recognition of the potential social benefits available from multi-use facilities. Williamson (1981) stated that "there are so many different types of organisations because transactions differ so greatly and efficiency is only realized if governance structures are tailored to the specific needs of each type of transaction." The legislative ownership discussion this far have attempted to frame the potential cooperation in a multi-use setting in the context of the broader social, political, and economic spheres. Next, the discussions also acknowledge and illuminate the perceptions and characteristics of the particular industries themselves. It appears clear that uncertainty and risk are large components of this discussion. These were reinforced and frequently voiced by the survey respondents in the German case study. It can be expected that the likelihood and form of collaboration in the near future will be shaped by how well this risk and uncertainty is addressed.

11.8 Regulation of Aquaculture Within the German Bight

The EEZ is a special area—it is not a state territory even if a coastal state has there sovereign rights and jurisdiction. This is an area where three legal systems come together: international law, law of the European Union and national law (Buck et al. 2003). There are no commercial aquaculture operations in the German EEZ and no approval procedure has been completed so far. Additionally, some sites are not suitable for aquaculture, especially because of nature conservation and shipping.

11.8.1 *Mariculture in the German Exclusive Economic Zone*

Mariculture in the Exclusive Economic Zone (EEZ) could be in the future an interesting completion of fishery, not least because of overfishing of natural stocks. Nevertheless, its legal questions are still not fully answered (for an overview of legal frame of mariculture see Kersandt 2012 as well as in BLFRG 2012; ECR 2006, 2007, 2008; EC 2000, 2008, 2011; SAG 1965; VüAs 1997).

11.8.1.1 The System of Law in the EEZ

The EEZ cannot be considered as a part of the state territory. It is a *sui generis* zone and the coastal state can only use it and regulate its use as outlined in the relevant provisions of the United Nations Convention on the Law of the Sea (Dahm et al. 1989; Gündling 1983). This effects the first restriction for the German law-maker. Furthermore, Germany as a member of the European Union, has to respect the European law. Although the EEZ is no sovereign state territory, the EU is allowed to issue the law: The EU has legislative authority in the area outside the members' territory, where the international public law gives such authority to the state, e.g. fisheries on the High Sea (Grabitz et al. 2010). Some directives and regulations refer to aquaculture, e.g. regulation concerning use of alien and locally absent species in aquaculture, directive on animal health requirements for aquaculture animals, products thereof and on the prevention of diseases or regulation on conditions for market placing and the import of aquaculture animals. Some general (i.e., not specific to aquaculture) rules are relevant to aquaculture, e.g. Marine Strategy Framework Directive, Water Framework Directive or EIA Directive.

The legislative authority usually belongs to the Federal Republic of Germany and not to the German States (*Länder*). It depends on the jurisdictional provisions of Article 74 GG, e.g. the law relating to economic matters (no. 11), deep-sea and coastal fishing (no. 17), and protection of nature and landscape management (no. 29) or management of water resources (no. 32).

11.8.1.2 The Approval Procedure

The basis for the approval procedure of aquaculture in the EEZ is Marine Facilities Ordinance (SeeAnlV), which is based on Federal Maritime Responsibilities Act. The agency deciding on the approval of mariculture in the EEZ is Federal Maritime and Hydrographic Agency (*Bundesamt für Seeschifffahrt und Hydrographie, BSH*). Aquaculture, as any other facility that is not purposed to produce or transmit energy, needs an approval. For energy projects, a plan approval procedure is mandatory. The approval, different than the plan approval, doesn't have the "concentration effect": the applicant needs to get all necessary permits on his own

(Dahlke 2002). Especially provisions of the German Federal Nature Conservation Act (Bundesnaturschutzgesetz - BNatSchG) are here determined, e.g. those about protected species (Art. 44 ff. BNatSchG), protected habitats (Art. 30 ff. BNatSchG) and Natura 2000 areas (Art. 31 ff. BNatSchG) (BNatSchG 2009).

An approval is a non-discretionary administrative act, i.e., it has to be granted when there are no reasons for denying approval (Dahlke 2002). According to Sect. 7 SeeAnlV the approval has to be denied when

- it is likely to impair the safety and efficiency of navigation or poses a threat to the marine environment or
- the requirements of regional planning or overriding military or other public or private predominant concerns are against the approval.

Before the approval has been granted the Federal Waterways and Shipping Agency (former Waterways and Shipping Directorate) has to give a declaration of agreement. It can only be denied if the facility impairs the safety and efficiency of navigation and it is not possible to prevent or compensate the detrimental effects through conditions or requirements, Sect. 8 SeeAnlV.

The term "marine environment" is explained in Sect. 5 subsection 6 no. 2 SeeAnlV. It refers to the definition of "pollution of the marine environment" in Article 1 (1) no. 4 UNCLOS. The approval is to be denied when the pollution gives rise to concern. Aquaculture projects in the EEZ can require environmental impact assessment. The Environmental Impact Assessment Act, which implements the EIA Directive, intends the examination only for intensive fish farming and not for other candidates like mussels or seaweeds. Whether the assessment is mandatory or not depends on the yearly fish amount: it is mandatory if this amount is larger than 2500 t. Otherwise, there is a general (500 t–2500 t) or site-related (250 t–500 t) preliminary examination of the environmental compatibility to undertake. Depending on the result, the assessment is to the end or the whole EIA has to be done.

11.8.1.3 The Sites for Mariculture Facilities

Spatial Planning Ordinance for the German EEZ in the North Sea (also in the Baltic Sea) regulates targets and principles of spatial planning. Marine aquaculture is identified as a meaningful economic sector in the future. Negative impacts of the mariculture on the marine environment shall be avoided. Facilities for mariculture shall be established preferably in combination with existing installations, Sect. 3.6.1 (1) and (2) Spatial Plan North Sea. Spatial planning has an effect on the site for mariculture facilities. In some areas, e.g. in shipping priority areas, measures and projects which are not compatible with the character of this area are not permitted, as stated in Sect. 3.1.1 (1) Marine Spatial Plan North Sea. In the reservation areas, other uses are also allowed, but the main use is given special consideration. This needs to be taken into account in a comparative evaluation assessment with other spatially significant planning tasks, measures and projects. Corresponding rules are provided for the Baltic Sea.

There are also other sites where mariculture is not allowed. In Natura 2000 areas, which are protected areas under national law, mariculture facilities are prohibited. 2005 the Eastern German Bight became a nature conservation area under German law, other sites—*Dogger Bank*, *Sylt Outer Reef* and *Borkum Reef Ground*—were nominated to the European Council. In Sect. 4 subsection 2 no. 1 of designating ordinance mariculture facilities are prohibited. It is likely that other ordinances will have the same regulation.

11.8.2 Approval procedure of offshore multi-use installations

Changing marine utilization patterns represent considerable challenge to society and governments. Indeed, the ongoing intense competition for ocean space leads and has led inevitably to disputes. As a case in point, the somewhat private ownership of ocean space, which usually is assigned via central government authorities, has fostered the raise of "client mentalities" of the ocean pioneers. This has resulted in a complex mix of ownership, associated commons and private property. Thus, the central question remains how to operationalise the multi-use dimension of offshore installations within marine spatial planning?

Centralized authority planning, such as showcased by the existing permitting procedure in the offshore realm in Germany that is charged by one lead agency (Federal Maritime and Hydrographic Agency) has given way to new forms of governing—tendency to define issues at only one scale and only one installation at time. Indeed, in the case of Germany, a highly comprehensive regulatory framework for offshore wind energy, but only a weak and uncertain framework for offshore aquaculture installations is in place. For the latter, technological as well as ecological standards are yet needed. In Fig. 11.45 we present a permitting procedure that possibly integrate multi-use installations within the same suite of permitting process. This is showcased by the integration of offshore wind farm installations and open ocean aquaculture. By acknowledging throughout the process the different demands, potential impacts and outcomes of each partner within a multi-use system, the permitting process could be streamlined and efficient. By this, the permit process would become more specific articulating societal choices about goals and their related social values in a multi-use context. Open issues pertain to e.g. who should be included in a balanced jurisdiction and what should that jurisdiction do? What criteria are relevant to opt for open ocean aquaculture and what are the implications of such criteria and how to include cross-border users? E. g. regions, where offshore wind farms are planned, are also important fishing regions of German, Belgian, Danish and Dutch fishermen.

In summary, the current gap between oceans as commons and ocean as private property as well as diverging views and pictures leads to a contested sea space.

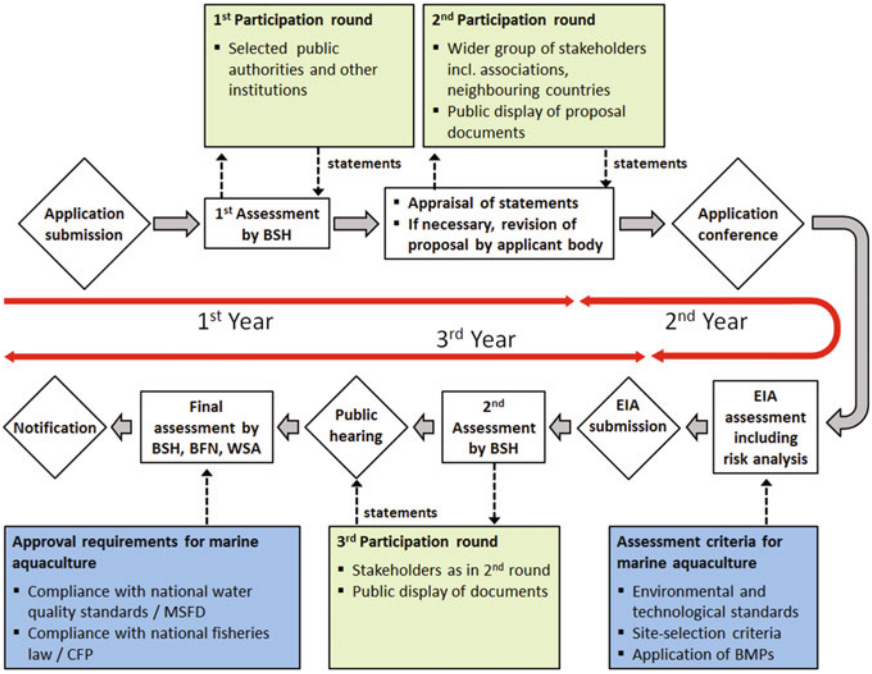

Fig. 11.45 Potential approval procedure of multi-use offshore installations (here exemplified by offshore wind farm and offshore aquaculture) in the German EEZ according to the Marine Facilities Ordinance. BFN = Bundesamt für Naturschutz (Federal Agency for Nature Conservation), BMP = Best Management Practice, BSH = Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency of Germany), CFP = Common Fisheries Policy, EIA = Environmental Impact Assessment, MSFD = Marine Strategy Framework Directive, WSA = Wasser- und Schifffahrtsdirektion (Waterways and Shipping Office) (modified after Wever 2011)

A more holistic, integrated approach to ocean management that acknowledges the interconnectedness of human and natural systems is timely. However, there is a high risk of failing in the current window-of-opportunity to integrate open ocean aquaculture within the emerging management of the marine realm. What is at odds is the management discourse of the politically powerful vs. newcomers, reaffirming the socially constructed nature of knowledge.

References

Abad, M., Ruiz, C., Martinez, D., Mosquera, G., & Sánchez, J. L. (1995). Seasonal variations of lipid classes and fatty acids in flat oyster, *Ostrea edulis*, from San Cibran (Galicia, Spain). *Comparative Biochemistry and Physiology, 110,* 109–118.

Ahn, O., Petrell, R. J., & Harrison, P. J. (1998). Ammonium and nitrate uptake by *Laminaria saccharina* and *Nereocystis luetkeana* originating from a salmon sea cage farm. *Journal of Applied Phycology, 10,* 333–340.

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future. *Aquatic Biosystems, 2014*(10), 8.

Bartlett, H. H. (1956). Fire, primitive agriculture, and grazing in the tropics. In W. L. Thomas (Ed.), *Man's role in changing the face of the earth* (pp. 692–720). Chicago and London: The University of Chicago Press.

Bartsch, I., Wiencke, C., Bischof, K., Buchholz, C., Buck, B. H., Eggert, A., et al. (2008). The genus Laminaria sensu lato: Recent insights and developments. *European Journal of Phycology, 43,* 1–86.

BLFRG. (2012). Basic law for the federal Republic of Germany in the revised version published in the Federal Law Gazette Part III, classification number 100-1, as last amended by the Act of 11.7.2012, Federal Law Gazette I, 1478.

Beamish, P. (1994). Joint vetures in LDCs: Partner selection and performance. *Management International Review, 34,* 60–74.

Beninger, P. G., & Lucas, A. (1984). Seasonal variations in condition, reproductive activity, and gross biochemical composition of two species of adult clam reared in a common habitat: *Tapes decussates* L. (Jeffreys) and *Tapes philippinarum* (Adams & Reeve). *Journal of Experimental Marine Biology and Ecology, 79,* 19–37.

Bilio, M. (2008). Controlled reproduction and domestication in aquaculture. The current state of the art. *Aquaculture Europe Part I-IV, 33,* 1–24.

Boghen, A. (1991). *Cold-Water aquaculture in Atlantic Canada*. New Brunswick: Canadian Institute for Research on Regional Development.

Brenner, M. (2009). *Site selection criteria and technical requirements for the offshore cultivation of Blue mussels (Mytilus edulis L.)*. PhD Thesis. Jacobs University Bremen, Germany.

Brenner, M., & Buck, B. H. (2010). Attachment properties of blue mussels (*Mytilus edulis* L.) byssus threads on culture-based artificial collector substrates. *Aquacultural Engineering, 42,* 128–139.

Brenner, M., Buck, B. H., & Köhler, A. (2007). New concepts for the multi-use of offshore wind farms and high quality mussel cultivation. *Global Aquaculture Advocate, 10,* 79–81.

Brenner, M., Buchholz, C., Heemken, O., Buck, B. H., & Köhler, A. (2012). Health and growth performance of the blue mussel (*Mytilus edulis* L.) from two hanging cultivation sites in the German Bight: a nearshore—offshore comparison. *Aquaculture International, 20,* 751–778.

Bridger, C. J., & Costa-Pierce, B. A. (2003). *Open ocean aquaculture: From research to commercial reality*. Baton Rouge, Louisiana, USA: The World Aquaculture Society.

BSH. (2016). *Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency), Maps of North Sea Stakeholders, CONTIS-Geodata (Continental Shelf Information System)*. Germany: Hamburg and Rostock.

Browne, L. (2001). Mariculture of the edible red alga *Palmaria palmata*. PhD thesis, Queen's University Belfast.

Buchholz, C., & Lüning, K. (1999). Isolated, distal blade discs of the brown alga Laminaria digitata form sorus, but not discs, near to the meristematic transition zone. *Journal of Applied Phycology, 11,* 579–584.

Buck, B. H. (2000). *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, 412. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

Buck, B. H. (2001). *Combined utilisation of wind farming and mariculture in the North Sea*. Biennial Report of Science Highlights at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, 33–39.

Buck, B. H. (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, 412. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

Buck, B. H. (2004). *Farming in a high energy environment: potentials and constraints of sustainable offshore aquaculture in the German Bight (North Sea)*. PhD thesis, University of Bremen, Germany.

Buck, B. H. (2007). Experimental trials on the feasibility of offshore seed production of the mussel Mytilus edulis in the German Bight: Installation, technical requirements and environmental conditions. *Helgoland Marine Research, 61,* 87–101.

Buck, B. H. (2017). Mytilid larval appearance and settlement at offshore wind farm sites in the German Bight—a trial to estimate multi-use potentials for bivalve seed collection and cultivation. Helgoland Marine Research.

Buck, B. H., & Buchholz, C. M. (2004a). The offshore-ring: A new system design for the open ocean aquaculture of macroalgae. *Journal of Applied Phycology, 16,* 355–368.

Buck, B. H., & Buchholz, C. M. (2004b). Support device for the cultivation of macro organisms in marine waters. Patents: PCT/DE2005/000234.

Buck, B. H., & Buchholz, C. M. (2005). Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. *Aquaculture, 250,* 674–691.

Buck, B. H., & Krause, G. (2012). Integration of aquaculture and renewable energy systems. In R. A. Meyers (Ed.), *Encyclopaedia of sustainability science and technology* (Vol. 1, pp. 511–533). Springer Science + Business Media LLC.

Buck, B. H., & Wunsch, M. (2005). Inspection device for under water constructions including a positioning system. Patent: DE 10 2005 020 070.

Buck, B. H., Ebeling, M., & Michler-Cieluch, T. (2010). Mussel cultivation as a co-use in offshore wind farms: Potentials and economic feasibility. *Aquaculture Economics and Management, 14,* 255–281.

Buck, B. H., Krause, G., & Rosenthal, H. (2004). Extensive open ocean aquaculture development within wind farms in Germany: The prospect of offshore co-management and legal constraints. *Ocean Coastal Management, 47,* 95–122.

Buck, B. H., Krause, G., Rosenthal, H., & Smetacek, V. (2003). Aquaculture and environmental regulations: The German situation within the North Sea. In A. Kirchner (Ed.), *International marine environmental law: Institutions, implementation and innovation. International environmental law and policies series of Kluwer Law international 64* (pp. 211–229). The Hague: Kluwer.

Buck, B. H., Walter, U., Rosenthal, H., & Neudecker, T. (2006a). The development of Mollusc farming in Germany: Past, present and future. *World Aquaculture Magazine, 6–11,* 66–69.

Buck, B. H., Berg-Pollack, A., Assheuer, J., Zielinski, O., & Kassen, D. (2006b). 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.

Buck, B. H., Thieltges, D., Walter, U., Nehls, G., & Rosenthal, H. (2005). Inshore-offshore comparison of parasite infestation in *Mytilus* edulis: Implications for open ocean aquaculture. *Journal of Applied Ichthyology, 21,* 107–113.

Buck, B. H., Krause, G., Michler-Cieluch, T., Brenner, M., Buchholz, C. M., & Busch, J. A. (2008a). Meeting the quest for spatial efficiency: Progress and prospects of extensive aquaculture within offshore wind farms. *Helgoland Marine Research, 62,* 269–281.

Buck, B. H., Zielinski, O., Assheuer, J., Wiemann, K., Hamm, C., & Kassen, D. (2008b). Technische Umsetzung von extensiven Marikulturanlagen in Windparks: Betrachtung der mechanischen Lasten (Technical realisation of extensive aquaculture in offshore wind farms: Calculation of mechanical loads). Project Report FV 174.

Buck, B. H., Dubois, J., Ebeling, M., Franz, B., Goseberg, N., Krause, G., et al. (2012). Projektbericht multiple nutzung und co-management von offshore-strukturen: Marine aquakultur und offshore windparks—Open Ocean Multi-Use (OOMU). Gefördert durch das BMU—Förderkennzeichen 325206. Projektleitung: IMARE GMBH Bremerhaven—Germany.

BNatSchG. (2009). Bundesnaturschutzgesetz, Federal Law Gazette I, 2542/2009, last amended by Federal Law Gazette I, 3154.

Byzio, A., Mautz, R., & Rosenbaum, W. (2005). *Energiewende in schwerer See? Konflikte um die Offshore-Windkraftnutzung*. München: Oekom.

Caers, M., Coutteau, P., & Sorgeloos, P. (2000). Impact of starvation and of feeding algal and artificial diets on the lipid content and composition of juvenile oyster (*Crassostrea gigas*) and clams (*Tapes philippinarum*). *Marine Biology, 136,* 891–899.

Carroll, G., Goodstein, J., & Gyenes, A. (1988). Organisations and the state: Effects of the institutional environment on agricultural cooperatives in hungary. *Administrative Science Quarterly, 33*, 233–256.

Chambers, M. D., & Howell, W. H. (2006). Preliminary information on cod and haddock production in submerged cages off the coast of New Hampshire, USA. *ICES Journal of Marine Science, 63,* 385–392.

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., et al. (2001). Integrating seaweeds into marine aquaculture systems: A key towards sustainability. *Journal of Phycology, 37,* 975–986.

Corey, P., Kim, J. K., Duston, J., & Garbary, D. J. (2014). Growth and nutrient uptake by *Palmaria palmata* integrated with Atlantic halibut in a land-based aquaculture system. *Algae, 29,* 35–45.

CWSS. (2002). *Shellfish fisheries. An overview of policies for shellfish fishing in the Wadden Sea*. Wilhelmshaven (Germany): Common Wadden Sea Secretariat.

Dahlke, C. (2002). Genehmigungsverfahren von Offshore-Windenergieanlagen nach der Seeanlagenverordnung. *NuR, 8,* 472–479.

Dahm, G., Delbrück, J., & Wolfrum, R. (1989). *Völkerrecht, Band I/1: Die Grundlagen. Die Völkerrechtssubjekte*. Berlin: de Gruyter.

Daniel, T. L. (1984). Unsteady aspects of aquatic locomotion. *American Zoology, 24,* 121–134.

Daniels, H. V., & Watanabe, W. O. (2010). *Practical flatfish culture and stock enhancement*. New Jersey: Wiley Blackwell.

Dare, P. J., Edwards, D. B., & Davies, G. (1983). *Experimental collection and handling of spat mussels (Mytilus edulis L.) on ropes for intertidal cultivation*. London: Ministry of Agriculture Fisheries and Food, Directorate of Fisheries Research.

Davenport, J., & Chen, X. (1987). A comparison of methods for the assessment of condition in the mussel (*Mytilus edulis* L.). *Journal of Molluscan Studies, 53,* 293–297.

Davies, I. M., Greathead, C., & Black, E. A. (2008). Risk analysis of the potential interbreeding of wild and escaped farmed cod (*Gadus morhua* Linnaeus). Reports and studies—Joint group of experts on the scientific aspects of marine. *Environmental Protection, 76,* 112–132.

De la Parra, A. M., García, O., & Fuencisla, S. J. (2005). Seasonal variation on the biochemical composition and lipid classes of the gonadal and storage tissues of *Crassostrea gigas* (Thunberg, 1794) in relation to the gametogenic cycle. *Journal of Shellfish Research, 24,* 457–467.

Denny, M. W. (1988). *Biology and the mechanics of the wave-swept environment*. New York: Princeton University Press.

Denny, M. W., Daniel, T. L., & Koehl, M. A. R. (1985). Mechanical limits to size in wave-swept organisms. *Ecological Monographs, 55,* 69–102.

Diederich, S., Nehls, G., van Beusekom, J. E. E., & Reise, K. (2004). Introduced Pacific oysters (Crassostrea gigas) in the northern Wadden Sea: Invasion accelerated by warm summers? *Helgoland Marine Research, 59,* 97–106.

D'Souza, G., Miller, D., Semmens, K., & Smith, D. (2004). Mine water aquaculture as an economic development strategy: Linking coal mining, fish farming, water conservation and recreation. *Journal of Applied Aquaculture, 15,* 159–172.

EC. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, December 22 2000, 1–73.

EC. (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy, OJ L 164, June 25 2008, 19–40.

EC. (2011). Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment, OJ L 335, 17.12.2011, 1–14; see also Directive 2014/52/ of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, OJ L 124, April 25 2014, 1–18.

ECR. (2006). European Council Directive 2006/88/EC of 24 October 2006 on animal health requirements for aquaculture animals and products thereof, and on the prevention and control of certain diseases in aquatic animals, OJ L 328, November 24 2006, 14–56.

ECR. (2007). European Council Regulation No 708/2007 of 11 June 2007 concerning use of alien and locally absent species in aquaculture, OJ L 168, June 28 2007, 1–17.

ECR. (2008). European Commission Regulation No 1251/2008 of 12 December 2008 implementing Council Directive 2006/88/EC as regards conditions and certification requirements for the placing on the market and the import into the Community of aquaculture animals and products thereof and laying down a list of vector species, OJ L 337, December 16 2008, 41–75.

Engle, C. R., Pomerleau, S., Fornshell, G., Hinshaw, J. M., Sloan, D., & Thompson, S. (2005). The economic impact of proposed effluent treatment options for production of trout *Oncorhynchus mykiss* in flow-through systems. *Aquacultural Engineering, 32,* 303–323.

FAO. (2004). *Food and Agricutlure Organization of the United Nations. Cultured aquatic species information programme*. *Salmo salar*. FAO Fisheries and Aquaculture Department. Retrieved October 12, 2016, from http://www.fao.org/fishery/culturedspecies/Salmo_salar/en

FAO. (2005). *Food and Agricutlure Organization of the United Nations. Cultured Aquatic Species Information Programme*. *Dicentrarchus labrax*. FAO Fisheries and Aquaculture Department. Retrieved October 12, 2016, from http://www.fao.org/fishery/culturedspecies/Dicentrarchus_labrax/en

Federal Agency for Agriculture and Food. (2007). Der Markt für Fischereierzeugnisse in der Bundesrepublik Deutschland im Jahre 2006: Bericht über die Versorgung der Bundesrepublik Deutschland mit Fischereiprodukten aus Eigenproduktion und Importen sowie die Exportsituation. Hamburg, Germany: Bundesanstalt für Landwirtschaft und Ernährung Referat 523 – Fischwirtschaft.

Fei, X. (2004). Solving the coastal eutrophication problem by large scale seaweed cultivation. *Hydrobiologia, 512,* 145–151.

Fiedler, G., Heuer, R., Koch, L., & Steinberg, R. (2011). *Windenergieanlagengeräusche als Stressor*. *Projektierung Biotechnologie WS 2010/11*. University of Applied Sciences Bremerhaven (Germany).

Fraser, A. J., Tocher, D. R., & Sargent, J. R. (1985). Thin-layer chromatography—Flame ionization detection and the quantification of marine neutral lipids and phospholipids. *Journal of Experimental Marine Biology and Ecology, 88,* 91–99.

Gallager, S. M., & Mann, R. (1986). Growth and survival of larvae of *Mercenaria mercenaria* (L.) and *Crassostrea virginica* (Gmelin) relative to broodstock conditioning and lipid content of eggs. *Aquaculture, 56,* 105–121.

Gloy, C. (2006). *Wirtschaftliche Bewertung einer kombinierten Windenergiegewinnung–Saatmuschel-Konsummuschelproduktion im Offshore-Bereich (Abschätzung von Kosten-Nutzen)*. Bremerhaven: CG Gloy.

Goseberg, N., Franz, B., & Schlurmann, T. (2012), The potential co-use of aquaculture and offshore wind energy structures. In *Proceedings of the Sixth Chinese-German Joint Symposium on Hydraulic and Ocean Engineering (CGJOINT 2012)* (Vol. 6, pp. 597–603), Keelung: National Taiwan Ocean University.

Grabitz, E., Hilf, M., & Nettesheim, M. (2010–2015). *Das Recht der Europäischen Union*. Munich, Germany: Beck.

Grandori, A., & Soda, G. (1995). Inter-firm networks: Antecedents, mechanisms and forms. *Organisational Studies, 16,* 183–214.

Griffin, R., & Krause, G. (2010). *Economics of wind farm-mariculture integration*. Working Paper, Department of Environmental and Natural Resource Economics, University of Rhode Island.

Grote, B. (2016). Bioremediation of aquaculture wastewater: evaluating the prospects of the red alga *Palmaria palmata* (Rhodophyta) for nitrogen uptake. *Journal of Applied Phycology*. doi:10.1007/s10811-016-0848-x

Grote, B., & Buck, B. H. (2017). The IMTA-approach for nutrient balanced aquaculture: Evaluating the potential of turbot (*Scophthalmus maximus*) and dulse (*Palmaria palmata*) from onshore RAS to offshore wind farm environments. *Aquaculture*.

Gündling, L. (1983). *Die 200 Seemeilen-Wirtschaftszone: Entstehung eines neuen Regimes des Meeresvölkerrechts*. Berlin, Germany: Springer.

Guiry, M. D., & Blunden, G. (1991). *Seaweed resources in Europe: Uses and potential*. Chichester, UK: Wiley.

Hatch, U., & Thai, C. F. (1997). A survey of aquaculture production economics and management. *Aquaculture Economics & Management, 1,* 13–27.

Hesley, C. (1997). Open ocean aquaculture: Chartering the future of Ocean farming. In *Proceedings of an International Conference, April 23–25, 1997, Maui, Hawaii*. UNIHI-Seagrant-CP-98-08, University of Hawaii Sea Grant College Program: Maui.

Hickman, R. W. (1992). Mussel cultivation. In E. Gosling (Ed.), *The mussel Mytilus: Ecology, physiology, genetics and culture* (pp. 465–510). Amsterdam/London: Elsevier.

Howell, W. H., & Chambers, M. D. (2005). Growth performance and survival of Atlantic halibut (*Hippoglossus hippoglossus*) growth in submerged net pens. In *Proceedings of the Contributed Papers of the 21 super(st) Annual, AAC* (pp. 35–37), St. Andrews, NB (Canada), Aquaculture Canada super(OM) 2004.

Hundt, M., Goseberg, N., Wever, L., Ebeling, M., Schlurmann, T., & Dubois, J. (2011). Multiple Nutzung und co-management von Offshore Strukturen: Marine Aquakultur und Offshore Windparks, Tagungsband, 8. FZK Kolloquium. Maritimer Wasserbau und Küsteningenieurwesen. Forschungszentrum Küste (FZK). *Gemeinsame Einrichtung der Leibniz Universität Hannover und der technischen Universität Braunschweig, 8,* 127–140.

Indergaard, M., & Minsaas, J. (1991). Animal and human nutrition. In M. D. Guiry & G. Blunden (Eds.), *Seaweed resources in Europe: Uses and potential* (pp. 21–64). Chichester, New York, Brisbane: John Wiley & Sons.

Jensen, Ø., Dempster, T., Thorstad, E. B., Uglem, I., & Fredheim, A. (2010). Escapes of fishes from Norwegian sea-cage aquaculture: Causes, consequences and prevention. *Aquatic Environmental Interaction, 1,* 71–83.

Jobling, M. (1988). A review of the physiological and nutritional energetics of cod, *Gadus morhua L.*, with particular reference to growth under farmed conditions. *Aquaculture, 70,* 1–19.

Johnson, S., & Houston, M. (2000). A reexamination of the motives and gains in joint ventures. *Journal of Finanyial and Quantitative Analysis, 35,* 67–85.

Joschko, T. J., Buck, B. H., Gutow, L., & Schröder, A. (2008). Colonisation of an artificial hard substrate by *Mytilus edulis* in the German Bight. *Marine Biology Research, 4,* 350–360.

Kain, J. M. (1979). A view of the genus *Laminaria*. *Oeeanography Marine Biology Annual Review, 17,* 101–161.

Kain, J. M. (1991). Cultivation of attached Seaweeds. In M. D. Guiry & G. Blunden (Eds.), *Seaweed resources in Europe: Uses and potential* (pp. 309–377). Chichester, UK: Wiley.

Kain, J. M., & Dawes, C. P. (1987). Useful European seaweeds: Past hopes and present cultivation. *Hydrobiologia, 151*(152), 173–181.

Kersandt, P. (2012). Rechtliche Rahmenbedingungen der Aquakultur im Meeres- und Küstenbereich von Nord- und Ostsee. In T. Bosecke, P. Kersandt & K. Täufer (Eds.), *Mereesnaturschutz. Erhaltung der Biodiversität und andere Herausforderungen im „Kaskadensystem" des Rechts* (pp. 181–206). Berlin: Springer.

Köller, J, Köppel, J., & Peters, W. (Eds.) (2006). *Offshore wind energy—Research on environmental impacts*. Springer.

Korsøen, O. J. (2011). Biological criteria for submergence of physostome (Atlantic salmon) and physoclist (Atlantic cod) fish in sea-cages. *Dissertation*, The University of Bergen, Bergen.

Krause, G., Buck, B. H., & Rosenthal, H. (2003). Multifunctional use and environmental regulations: potentials in the offshore aquaculture development in Germany. In A. Sjoestroem (Ed.), *Rights and Duties in the Coastal Zone, Proceedings of the Multidisciplinary Scientific Conference on Sustainable Coastal Zone Management Rights and Duties in the Coastal Zone, 12–14 June 2003*. Sweden: Stockholm.

Krause, G., Griffin, R. M., & Buck, B. H. (2011). Perceived concerns and advocated organisational structures of ownership supporting 'Offshore Wind Farm – Mariculture Integration'. In G. Krause (Ed.), *From turbine to wind farms: Technical requirements and spin off products* (pp. 203–218). Rijeka, Croatia: InTech, Open Access Publisher.

Krause, G., Brugere, C., Diedrich, A., Troell, M., Ebeling, M. W., Ferse, S. C., et al. (2015). A Revolution without people? Closing the people-policy gap in aquaculture development. *Aquaculture, 447,* 44–55.

Krone, R. (2012a). Artificial habitat in polyhedron for crustaceans in marine soft bottoms and application (Künstliches Habitat in Polyederform für Krebstiere auf marinen Weichböden und Anwendung). German Patent DE102010049049B3.

Krone, R. (2012b). Offshore wind power reef effects and reef fauna roles. *Dissertation*, University Bremen.

Krone, R., & Krämer, P. (2011). Device for colonizing and harvesting marine hardground animals, (Vorrichtung zur Ansiedelung und Ernte von marinen Hartbodentieren); German Patent DE102009058278B3; United States patent US020110139083A1.

Krone, R., & Krämer, P. (2012). Transportable device for colonizing and harvesting invertebrates and its use, (Transportierbare Vorrichtung zur Ansiedlung und Erntung von wirbellosen Tieren und Anwendung davon. German Patent DE102009049083B3; Canadian patent CA000002764735A1; international patent WO002011042003A1.

Krone, R., & Schröder, A. (2011). Wrecks as artificial lobster habitats in the German Bight. Helgoland marine research. doi: 10.1007/s10152-010-0195-2

Krone, R., Schmalenbach, I., & Franke, H. D. (2013). Lobster settlement at the offshore wind farm Riffgat, German Bight (North Sea). WinMon. BE Conference, Environmental impact of offshore wind farms, Royal Belgian Institute of Natural Sciences, Brussels, Belgium, 26 November 2013–28 November 2013.

Krone, R., Schröder, A., & Krämer, P. (2012). Device for developing habitats in the underwater area of an offshore construction, (Vorrichtung zur Habitaterschließung im Unterwasserbereich eines Offshore-Bauwerks). German Patent DE102010021606B4; international patent WO002011147400A3.

Kumar, M. V. (2007). Asymmetric wealth gains in joint ventures: Theory and evidence. *Finance Research Letters, 4*, 19–27.

Laing, I., Walker, P., & Areal, F. (2006). Return of the native—Is European oyster (*Ostrea edulis*) stock restoration in the UK feasible? *Aquatic Living Resources, 19,* 283–287.

Lanari, D., D'Agaro, E., & Ballestrazzi, R. (2002). Growth parameters in European sea bass (*Dicentrarchus labrax* L.): Effects of live weight and water temperature. *Italian Journal of Animal Science, 1,* 181–185.

Langan, R., & Horton, F. (2003). Design, operation and economics of submerged longline mussel culture in the open ocean. *Bulletin of the Aquaculture Association of Canada, 103,* 11–20.

Le Gall, L., Pien, S., & Rusig, A. M. (2004). Cultivation of *Palmaria palmata* (Palmariales, Rhodophyta) from isolated spores in semi-controlled conditions. *Aquaculture, 229,* 181–191.

Liu, Y., & Sumaila, R. U. (2007). Economic analysis of netcage versus sea-bag production systems for salmon aquaculture in British Columbia. *Aquaculture Economics & Management, 11,* 371–395.

Løvstad-Holdt, S., & Kraan, S. (2011). Bioactive compounds in seaweed: functional food applications and legislation. *Journal of Applied Phycology, 23,* 543–597.

Lutges, S., & Holzfuss, H. (2006). Integrates coastal zone management in Germany: Assessment and steps towards a national ICZM strategy. German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Lüning, K. (1979). Growth strategies of three *Laminaria* species (Phaeophyceae) inhabiting different depth zones in the sublittoral region of Helgoland (North Sea). *Marine Ecology Progress Series, 1,* 195–207.

Lüning, K. (1990). *Seaweeds: Their environment, biogeography, and ecophysiology*. Chichester, New York, Brisbane: Wiley.

Lüning, K. (2001). SEAPURA: Seaweeds purifying effluents from fish farms, an EU project coordinated by the Wattenmeerstation Sylt, Wadden Sea Newsletter, 20–21.

Lüning, K., & Pang, S. J. (2003). Mass cultivation of seaweeds: current aspects and approaches. *Journal of Applied Phycology, 15,* 115–119.

Lüning, K., Wagner, A., & Buchholz, C. (2000). Evidence for inhibitors of sporangium formation in *Laminaria digitata* (Phaeophyceae) during the season of rapid growth. *Journal of Phycology, 36,* 1129–1134.

Matos, J., Costa, S., Rodrigues, A., Pereira, R., & Sousa-Pinto, I. (2006). Experimental integrated aquaculture of fish and red seaweeds in Northern Portugal. *Aquaculture, 252,* 31–42.

Matthiessen, G. C. (2001). *Oyster culture*. London: Wiley-Blackwell.

Mc Hugh, D. J. (2003). A guide to the seaweed industry. FAO Fisheries Technical Papers T441.

Mee, L. (2006). *Complementary benefits of alternative energy: Suitability of offshore wind farms as aquaculture sites*. Report of Project 10517, commissioned by Seafish.

Michler-Cieluch, T. (2009). *Co-management processes in integrated coastal management—The case of integrating marine aquaculture in offshore wind farms*. Hamburg: University of Hamburg, Department of Integrative Geography.

Michler-Cieluch, T., & Krause, G. (2008). Perceived concerns and possible management strategies for governing wind farm-mariculture integration. *Marine Policy, 32,* 1013–1022.

Michler-Cieluch, T., & Kodeih, S. (2008). Mussel and seaweed cultivation in offshore wind farms: an opinion survey. *Coastal Management, 36,* 392–411.

Michler-Cieluch, T., Krause, G., & Buck, B. H. (2009a). Reflections on integrating operation and maintenance activities of offshore wind farms and mariculture. *Ocean and Coastal Management, 52,* 57–68.

Michler-Cieluch, T., Krause, G., & Buck, B. H. (2009b). Marine aquaculture within offshore wind farms: Social aspects of multiple use planning. *GAIA, 18,* 158–162.

Mittendorf, K., Nguyen, B., & Zielke, W. (2001). User manual waveloads—A computer program to calculate wave loading on vertical and inclined tubes. Institut für Strömungsmechanik und Elektron. Rechnen im Bauwesen, Universität Hannover. Retrieved October 12, 2016, from

Moksness, E., Kjorsvik, E., & Olsen, Y. (2004). *Culture of cold-water marine fish*. London: Wiley-Blackwell.

Molenaar, F. J., & Breeman, A. M. (1997). Latitudinal trends in the growth and reproductve seasonality of *Delesseria sanguinea, Membranoptera alata and Phycodrys rubens* (RHODOPHYTA). *Journal of Phycology, 33,* 330–343.

Morgan, K. C., & Simpson, F. J. (1981). The cultivation of Palmaria palmata. Effect of light intensity and temperature on growth and chemical composition. *Botanica Marina, 24*, 547–552.

Morgan, K. C., Wright, J. L., & Simpson, F. J. (1980a). Review of chemical constituents of the red alga *Palmaria palmata* (dulse). *Economic Botany, 34,* 27–50.

Morgan, K. C., Shacklock, P. F., & Simpson, F. J. (1980b). Some aspects of the culture of *Palmaria palmata* in greenhouse conditions. *Botanica Marina, 23*, 765–770.

Morison, J. R., O'Brien, M. P., & Schaaf, S. A. (1950). The force exerted by surface waves on piles. *Petroleum Transactions, AIME 2846, 189*, 149–157

Neori, A., Chopin, T., Troell, M., Buschmann, A. H., Kraemer, G. P., & Halling, C. (2004). Integrated aquaculture: Rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture, 231,* 361–391.

Newkirk, G. F., Muise, B., & Enright, C. T. (1995). Culture of the Belon oyster, *Ostrea edulis*, in Nova Scotia. In A. D. Boghen (Ed.), *Cold-water aquaculture in Atlantic Canada*. Moncton, Canada: Canadian Institute for Research on Regional Development.

Nielsen, B. (2010). Strategic fit, contractual, and procedural governance in alliances. *Journal of Business Research, 63*, 682–689.

NKüFischO. (2006). Niedersächsische Küstenfischereiordnung, Nds. GVBl. S. 108—VORIS 79300.

Noble, B. (2000). Institutional criteria for co-management. *Marine Policy, 24*(1), 69–77.

OFT. (2010). *Aquapod—A submergible fish cage*. Searsmont, USA: Ocean Farm Technologies.

Özbilgina, H., & Glass, C. W. (2004). Role of learning in mesh penetration behaviour of haddock (*Melanogrammus aeglefinus*). *ICES Journal of Marine Science: Journal du Conseil, 61,* 1190–1194.

Pang, S. J., & Lüning, K. (2004). Tank cultivation of the red alga *Palmaria palmata*: Effects of intermittent light on growth rate, yield and growth kinetics. *Journal of Applied Phycology, 16,* 93–99.

Pang, S. J., & Lüning, K. (2006). Tank cultivation of the red alga *Palmaria palmata*: Year-round induction of tetrasporangia, tetraspore release in darkness and mass cultivation of vegetative thalli. *Aquaculture, 252,* 20–30.

Pazos, A. J., Ruíz, C., García-Martín, O., Abad, M., & Sánchez, J. L. (1996). Seasonal variations of the lipid content and fatty acid composition of *Crassostrea gigas* cultured in El Grove, Galicia, N.W. Spain. *Comparative Biochemistry and Physiology, 114,* 171–179.

Pelz, P. (1974). Rationalisierung aus unternehmerischer Sicht: Vorbereitung und technischwirtschaftliche Beurteilung. In P. Pelz (Ed.), *Die Priorität der Rationalisierung im Unternehmen* (pp. 58). Düsseldorf/Berlin, Germany: Verein Deutscher Ingenieure, VDI-Bildungswerk.

Person-Le Ruyet, J., Buchet, V., Vincent, B., Le Delliou, H., & Quemener, L. (2006). Effects of temperature on the growth of pollack (*Pollachius pollachius*) juveniles. *Aquaculture, 251,* 340–345.

Perez, P., Kaas, R., Campello, F., Arbault, S., & Barbaroux, O. (1992). *La culture des algues marines dans le monde*. Nantes, France: IFREMER.

Petrell, R. J., & Alie, S. Y. (1996). Integrated cultivation of salmonids and seaweeds in open systems. *Hydrobiologia, 326,* 67–73.

Pogoda, B. (2012). Farming the High Seas: Biological performance of the offshore cultivated oysters *Ostrea edulis* and *Crassostrea gigas* in the North Sea. *Dissertation*, Marine Zoology of the Department of Biology & Chemistry, University of Bremen.

Pogoda, B., Buck, B. H., & Hagen, W. (2011). Growth performance and condition of oysters (Crassostrea gigas and Ostrea edulis) farmed in an offshore environment (North Sea, Germany). *Aquaculture, 319,* 484–492.

Pogoda, B., Grote, B., & Buck, B. H. (2015). Aquakultur-Site-Selection für die nachhaltige und multifunktionale Nutzung von marinen Gebieten in stark genutzten Meeren am Beispiel der Nordsee—Offshore Site-Selection. Gefördert durch das BMELV—Förderkennzeichen GZ: 511-06.01-28-1-73.009-10.

Pogoda, B., Buck, B. H., Saborowski, R., & Hagen, W. (2013). Biochemical and elemental composition of the offshore-cultivated oysters *Ostrea edulis* and *Crassostrea gigas*. *Aquaculture, 400,* 53–60.

Pogoda, B., Jungblut, S., Buck, B. H., & Hagen, W. (2012). Infestation of oysters and mussels by mytilicolid copepods: Differences between natural coastal habitats and two offshore cultivation sites in the German Bight. *Journal of Applied Ichthyology, 28*(5), 756–765.

Polk, M. (1996). Open Ocean Aquaculture. In *Proceedings of an International Conference, May 8–10, 1996, Portland, Maine*. UNHMP-CP-SG-96-9, Portland, New Hampshire/Maine Sea Grant College Program.

Pomeroy, R. S., Parks, J. E., & Balboa, C. M. (2006). Farming the reef: Is aquaculture a solution for reducing fishing pressure on coral reefs? *Marine Policy, 30,* 111–130.

Raman-Nair, W., & Colbourne, D. B. (2003). Dynamics of a mussel longline system article in aquacultural. *Engineering, 27,* 191–212.

Rhode Island Coastal Resources Management Council. (2010). Rhode Island Ocean Special Area Management Plan.

Rick, H. J., Rick, S., Tillmann, U., Brockmann, U., Gaertner, U., Duerselen, C., et al. (2006). Primary productivity in the German bight (1994–1996). *Estuaries and Coasts, 29,* 4–23.

Robinson, D. (2008). Strategic alliances and the boundaries of the firm. *The Review of Financial Studies, 21*, 649–681.

Rosenberg, R., & Loo, L. O. (1983). Energy flow in a *Mytilus edulis* culture in western Sweden. *Aquaculture, 35,* 151–167.

Rosenlund, G., & Skretting, M. (2006). Worldwide status and perspective on gadoid culture. *ICES Journal of Marine Science, 63,* 194–197.

Ruíz, C., Martinez, D., Mosquera, G., Abad, M., & Sánchez, J. L. (1992). Seasonal variations in condition, reproductive activity and biochemical composition of the flat oyster, *Ostrea edulis*, from San Cibran (Galicia, Spain). *Marine Biology, 112,* 67–74.

SAG. (1965). Seeaufgabengesetz of 24.5.1965, Federal Law Gazette 1965 II p. 833, last amended by Act of 19.10. 2013, Federal Law Gazette I p. 3836.

Sahr, J. (2006). *Wind und Meer: Küstenproduktion von morgen. Anregungen für Marikultur in Offshore Windparks*. Bremerhaven: CG Gloy.

Sanderson, J. C., Dring, M. J., Davidson, K., & Kelly, M. S. (2012). Culture, yield and bioremediation potential of *Palmaria palmata* (*Linnaeus)* Weber & Mohr *and Saccharina latissima* (*Linnaeus*) C.E. Lane, C. Mayes, Druehl & G.W. Saunders adjacent to fish farm cages in northwest Scotland. *Aquaculture, 354–355,* 128–135.

Scarratt, D. (1993). *A handbook of northern Mussel culture*. Montague: Island Press.

Schmalenbach, I., & Krone, R. (2011). Secondary use of offshore wind farms—Settlement of juvenile European lobsters (*Homarus gammarus*). IMARE-Conference "Marine Resources and Beyond", 5–7 September 2011, Bremerhaven, Germany.

Schmalenbach, I., Mehrtens, F., Janke, M., & Buchholz, F. (2011). A mark-recapture study of hatchery-reared juvenile European lobsters, *Homarus gammarus*, released at the rocky island of Helgoland (German Bight, North Sea) from 2000 to 2009. *Fisheries Research, 108,* 22–30.

SFA. (2008). Annual data for mussel harvest in Lower Saxony (Germany) in the years 1950–2007 provided by the State Fisheries Agency Bremerhaven (Germany).

Smaal, A. C., Kater, B. J., & Wijsman, J. (2009). Introduction, establishment and expansion of the Pacific oyster *Crassostrea gigas* in the Oosterschelde (SW Netherlands). *Helgoland Marine Research, 63,* 75–83.

Sørensen, H. C., Hansen, J., & Vølund, P. (2001). Experiences from the establishment of Middelgrunden 40 MW offshore wind farm. In *Proceedings of the European Wind Energy Conference*, 2–6 July, Copenhagen, Denmark: EWEA.

Stelzenmüller, V., Diekmann, R., Bastardie, F., Schulze, T., Berkenhagen, J., Kloppmann, et al. (2016). Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: A first socio-economic scoping. *Journal of Environmental Management, 183*, 794–805. doi dx.doi.org/10.1016/j.jenvman.2016.08.027.

Stickney, R. R. (1998). Joining forces with industry—open ocean aquaculture. In *Proceedings of the Third Annual International Conference*, May 10–15, Corpus Christi, Texas. TAMU-SG-99-103, Corpus Christi, Texas Sea Grant College Program.

Sturrock, H., Newton, R., Paffrath, S., Bostock, J., Muir, J., Young, J., et al. (2008). Prospective analysis of the aquaculture sector in the EU. Part 2: Characterisation of emerging aquaculture systems. Seville, Spain: Institute for Prospective Technological Studies.

Subandar, A., Petrell, R. J., & Harrison, P. J. (1993). Laminaria culture for reduction of dissolved inorganic nitrogen in salmon farm effluent. *Journal of Applied Phycology, 5,* 455–463. doi:10.1007/BF02182738

Thieltges, D. W., Krakau, M., Andresen, H., Fottner, S., & Reise, K. (2006). Macroparasite community in molluscs of a tidal basin in the Wadden Sea. *Helgoland Marine Research, 60,* 307–316.

Tortell, P. (1976). A new rope for mussel farming. *Aquaculture, 8,* 383–388.

Treasurer, J. W., Sveier, H., Harvey, W., Allen, R., Cutts, C. J., Mazorra de Quero, C., et al. (2006). Growth, survival, diet, and on-growing husbandry of haddock *Melanogrammus aeglefinus* in tanks and netpens. *ICES Journal of Marine Science, 63,* 376–384.

Troell, M., Rönnbäck, P., Halling, C., Kautsky, N., & Buschmann, A. (1999). Ecological engineering in aquaculture: Use of seaweeds for removing nutrients from intensive mariculture. *Journal of Applied Phycology, 11,* 89–97.

VüAs. (1997). Verordnung über Anlagen seewärts der Begrenzung des deutschen Küstenmeeres of 23.01.1997, Federal Law Gazette I p. 57, last amended by Ordinance of 29.8.2013 Federal Gazette of 30.08.2013.

Vollstedt, B. (2011). The role of perceptions and networks in multiple marine resource use: Integrating aquaculture and offshore wind farms in the North Sea. Master thesis University Kiel.

Walne, P. R., & Mann, R. (1975). Growth and biochemical composition in *Ostrea edulis* and *Crassostrea gigas*. In H. Barnes (Ed.), *Proceedings of 9th EMBS Aberdeen* (pp. 587–607).

Walter, U., & Liebezeit, G. (2003). Efficiency of blue mussel (*Mytilus edulis*) spat collectors in highly dynamic tidal environments of the Lower Saxonian coast (southern North Sea). *Biomolecular Engineering*, *20,* 407–411.

Walter, U., & Liebezeit, G. (2001). Abschlußbericht des Projektes: Nachhaltige Miesmuschel-Anzucht im niedersächsischen Wattenmeer durch die Besiedlung natürlicher und künstlicher Substrate. Forschungszentrum Terramare.

Walter, U., Buck, B. H., & Rosenthal, H. (2002). Marikultur im Nordseeraum: Status Quo, Probleme und Tendenzen. In J. L. Lozán, E. Rachor, & K. Reise (Eds.), *Warnsignale aus Nordsee & Wattenmeer: eine aktuelle Umweltbilanz* (pp. 122–131). Hamburg: Büro Wiss. Auswertungen.

Weiss, M., & Buck, B. H. (2017). Blue Mussel *(Mytilus edulis)* Meat as a Partial Fish Meal Replacement for the Diet in Turbot Aquaculture. *Journal of Applied Ichthyology*.

Weiss, M., Wittke, S., Greim Fish Consulting, WeserWind, Louis Schoppenhauer GmbH & Co. KG. (2012). NutriMat: Nutritional material from fouling organisms—Analyse der Nutzungsmöglichkeiten von biologischem Aufwuchs von künstlichen Hartsubstraten für die Gewinnung alternativer Protein- und Lipidressourcen. Bremerhaven, Germany: Imare.

Werner, A., & Dring, M. (2011). *Aquaculture explained no 27*. BIM—Irish Sea Fisheries Board: Cultivating Palmaria palmata.

Wever, L. (2011). *The emergence of multi-use ocean governance: Potentials and constraints for offshore windfarm-mariculture integration in Germany*. International Conference "Marine Resources and Beyond 2011", September 5-7 2011, Bremerhaven, Germany. Book of Abstracts. 46 p.

Wever, L., Buck, B. H., & Krause, G. (2014). Lessons from stakeholder dialogues on marine aquaculture in offshore wind farms: Perceived potentials, constraints and research gaps. *Marine Policy, 51,* 251–259.

Whitmarsh, D. J., Cook, E. J., & Black, K. D. (2006). Searching for sustainability in aquaculture: An investigation into the economic prospects for an integrated salmon-mussel production system. *Marine Policy, 30,* 293–298.

Whyte, J. N. C., Englar, J. R., & Carswell, B. L. (1990). Biochemical composition and energy reserves in *Crassostrea gigas* exposed to different levels of nutrition. *Aquaculture, 90,* 157–172.

Wildish, D. J., & Kristmanson, D. D. (1984). Importance to mussels of the benthic boundary layer. *Canadian Journal of Fisheries and Aquatic Sciences, 41,* 1618–1625.

Wildish, D. J., & Kristmanson, D. D. (1985). Control of suspension feeding bivalve production by current speed. *Helgoländer Wiss Meeresunters, 39,* 237–243.

Williamson, O. (1979). Transaction-cost economics: The governance of contractual relations. *Journal of Law and Economics, 22,* 233–261.

Williamson, O. (1981). The economics of organisation: The transaction cost approach. *American Journal of Sociology, 87,* 548–577.

Wiltshire, K. H., & Manly, B. F. J. (2004). The warming trend at Helgoland Roads, North Sea: Phytoplankton response. *Helgoland Marine Research, 58,* 269–273.

Chapter 12
The EU-Project "TROPOS"

Nikos Papandroulakis, Claudia Thomsen, Katja Mintenbeck, Pedro Mayorga and José Joaquín Hernández-Brito

Abstract The global population is growing and the demand for food and energy is steadily increasing. Coastal space all over the world becomes increasingly limited and near-shore resources are often already heavily exploited. The use of offshore regions may provide new opportunities, but also involves major challenges such as the development of designs and technologies suitable for offshore condition. The floating TROPOS 'Green & Blue' modular multi-use platform concept introduced in this chapter is especially designed for offshore conditions and provides solutions for the problems and obstacles involved in "moving offshore". The Green & Blue platform concept integrates fish and algae aquaculture with a wind farm. The floating multi-use approach allows for platform operation in deep waters and the promotion of synergies such as joint logistics, shared infrastructure and services, thereby making the use of offshore resources viable and profitable.

N. Papandroulakis (✉)
Hellenic Centre for Marine Research, Institute of Marine Biology Biotechnology and Aquaculture, AquaLabs, Gournes, Heraklion GR 71500, Crete, Greece
e-mail: npap@hcmr.gr

C. Thomsen
Phytolutions GmbH, Campus Ring 1, Bremen 28759, Germany

K. Mintenbeck
Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Integrative Ecophysiology/Marine Aquaculture, Am Handelshafen 12, Bremerhaven 27570, Germany

P. Mayorga
EnerOcean S.L, Bulevar Louis Pasteur 5, Of.321, Málaga 29010, Spain

J.J. Hernández-Brito
PLOCAN (Consorcio Para La Construcción, Equipamiento Y Explotación de La Plataforma Oceánica de Canarias), Crta. de Taliarte, s/n, Telde 35200, Spain

B.H. Buck and R. Langan (eds.), *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, DOI 10.1007/978-3-319-51159-7_12

12.1 Introduction

12.1.1 *Moving Offshore*

Coastal space all over the world has become increasingly limited and near-shore resources are often already heavily exploited. As a consequence, there is a growing call to move towards offshore aquaculture technologies. The advantages of offshore aquaculture compared to coastal aquaculture include, e.g., fewer restrictions (environmental, geographical, political), less competition for space with other activities (Ryan 2004), and better environmental conditions which result in improved fish growth, more efficient feed conversion, and a lower risk for pathogen infection (Ryan et al. 2007). Additionally, moving from protected areas of restricted water circulation to more exposed sea conditions allows farms with higher production capacity without increasing environmental impacts (Lu et al. 2014). However, moving offshore involves some major challenges, among others, high costs for the required infrastructure and transportation, more difficult access to services, supply and markets, and the need to adapt methodologies and procedures to offshore conditions. The best approach to overcome these problems is the development of shared solutions with other offshore sectors, i.e. to find and make use of synergies for a common use of sea space, infrastructure, resources (energy, water, supplies), services (maintenance, monitoring, surveillance) and transportation.

Accordingly, the European Union has launched the “The Ocean of Tomorrow” call in the 7th Framework Programme (FP7) for Research and Development, with one topic being “Multi-use Offshore Platforms” (OCEAN 2011.1). In total, three projects were selected and received funding for the design of multi-use offshore platforms: H2OCEAN, MERMAID and TROPOS. The latter one, the TROPOS project, is presented in this chapter.

12.1.2 *About TROPOS*

The full title of the TROPOS project is “*Modular Multi-use Deep Water Offshore Platform Harnessing and Servicing Mediterranean*, *Subtropical and Tropical Marine and Maritime Resources*”. TROPOS had a total project duration of 3 years (January 2012–January 2015). The project involved 20 partners from 9 different countries and was coordinated by PLOCAN (PLataforma Oceánica de las CANarias, Gran Canaria, Canary Islands, Spain).

The TROPOS project aimed at developing a floating modular multi-use platform system for use in deep waters, with an initial focus on Mediterranean and subtropical regions (Quevedo et al. 2012). Multi-use offshore platforms should allow for sustainable and eco-friendly uses and a synergistic exploitation of oceanic resources. A floating design facilitates access to deep sea areas and resources where deployment of conventional platform types is not possible. A modular multi-use

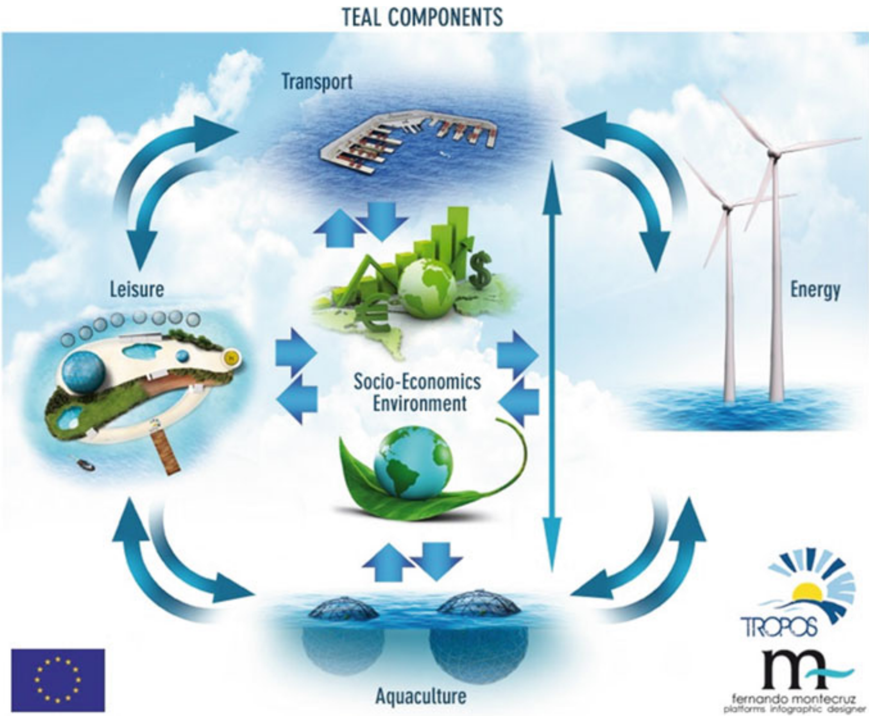

Fig. 12.1 The TROPOS TEAL (Transport, Energy, Aquaculture, Leisure) components (Fernando Montecruz for the TROPOS project)

approach allows for the integration of a range of functions from different sectors. In the case of TROPOS, functions of four different sectors were integrated, namely *Transport*, *Energy*, *Aquaculture*, and *Leisure* (in short: TEAL; Fig. 12.1). *Marine Transport* (T) provides critical services to the society ranging from building commercial and leisure ships, shipping of goods and fuel around the world, passenger transfer, to servicing offshore structures. The development of renewable *Energies* (E) is essential to address the dramatic depletion of fossil fuel reserves and to fight climate change, which has become one of the most critical global issues in recent years. Natural marine living resources are already heavily exploited, while the demand for these resources is steadily increasing. To reduce the fishing pressure on wild stocks, the demand needs to be increasingly met additionally by *Aquaculture* (A). The tourism industry represents the third largest socio-economic activity in the EU and space is needed for the development of new *Leisure* (L) activities. Not only in Europe, but all over the world there is an increasing demand for innovative, eco-friendly solutions in the tourism sector.

The development process involved successive iterations to find feasible solutions restricted by technical, environmental and socio-economic constrains. A multidisciplinary and cross sectorial team of specialists developed several tools to explore suitable sites, combinations of resources, synergies, structural solutions and their technical, environmental and socio-economic viabilities. The analyses also included logistics, security, installation, operational, decommissioning and maintenance requirements. The outcome of the development process included different theoretical platform concepts, designed and specified in great detail based on simulations and models which were validated by experimental tests of realistic small-scale models. The developed TROPOS concepts included the so-called "Sustainable Sevice Hub", "Leisure Island" and the "Green & Blue" concept. The latter one, the Green & Blue concept, integrates offshore aquaculture and renewable energies (Papandroulakis et al. 2014).

12.1.3 Aquaculture in TROPOS

Human population is growing and the demand for seafood is steadily increasing. Marine organisms are a source of high quality nutrients (proteins, essential fatty acids, vitamins, minerals, etc.) which are fundamental in human nutrition, but are also an important component in animal feeds and non-food sectors (e.g. cosmetic products). As the availability of natural resources is limited, an increasing amount of the demand has to be covered by aquaculture products. Aquaculture is the fastest growing economic area in the food industry sector and the proportion of the world's food fish coming from aquaculture has risen in 2006 to almost half (FAO 2014). With the increasing demand for seafood the fish-farming industry will have to continue this trend (Cressey 2009). Accordingly, the integration of aquaculture in the TROPOS multi-use concepts was of major interest.

The European aquaculture sector has access to dynamic and cutting-edge research and technologies, advanced equipment and fish feed. Production currently meets the requirements for environmental protection, and the final products are traceable and meet high quality standards. The European Aquaculture Technology and Innovation Platform (EATiP) has set several objectives for the sector to achieve by 2030. Particularly for the Mediterranean, the target is to increase production by 200%. This production scenario will increase the current production from 230,000 to 690,000 t. To meet this objective, EATiP has defined the development of efficient technologies (such as developed in the scope of TROPOS) to support continued growth as one of its strategic goals.

Considering the expected growth of the aquaculture industry and the market globalization, the targeted species, regardless of group (i.e. fish, shellfish, algae), have to shift to those with global distribution and market. The target species should be a fast growing and well adapted to the environmental conditions offshore and clear oceanic waters. Among finfish, typical target species are large, fast growing pelagic and deep demersal species, such as the greater amberjack and the wreckfish; both species recently became targets for developing innovative and efficient rearing technologies.

In TROPOS, the main focus was not only on finfish but also on microalgae aquaculture.

Microalgae are not only of high interest in the food and feed sectors, but also for the production of biofuel (Enzing et al. 2014). The market volume and value of microalgae range over a broad scale from 1,000–5,000 €/t for high volume biofuels to 10,000–35,000 €/t for high value food. The value of microalgae used for pharmaceuticals is even higher. In the aquaculture industry microalgae are important as feed for early developmental stages of several species (larvae of molluscs, echinoderms, crustaceans, fish), with a worldwide annual production of approximately 10,000 t/year and a market value of about 30–250 €/kg. Approximately $^{1}/_{5}$ of this biomass is used for larval stages of fish and shellfish reared in hatcheries (Muller-Feuga 2004). The most frequently used species are *Chlorella*, *Tetraselmis*, *Dunaliella, Isochrysis*, *Pavlova*, *Nannochloropsis*, *Phaeodactylum*, *Chaetoceros*, *Skeletonema* and *Thalassiosira* (Spolaore et al. 2006).

The greatest demand for microalgae lies in its potential to replace the current sources of PUFA (PolyUnsaturated Fatty Acids; Omega 3/6 fatty acids). The increasing public debate on the use of fishmeal for aquaculture puts microalgae in the focus as substitute for fishmeal, and Omega-3 industries increasingly produce concentrated EPA (eicosapentaenoic acid) and DHA (Docosahexaenoic acid) oils for human consumption.

Microalgae (and macroalgae) are also considered as possible substitute for fossil fuels. Despite a large body of research in the area of photosynthesis for carbon sequestration, little work has been done to develop practical algae production systems that do not ignore land availability limitations and can be installed at any location for the production of fuels, food and animal feed. Offshore algae production could fill that gap and allow the energy and cost efficient high volume conversion into biofuels.

12.2 The Conceptual Approach of TROPOS

12.2.1 General Platform Design

The key characteristics of the TROPOS platform concepts are (i) the floating design which enables platform operation in deep waters, (ii) the multi-use concept which supports the integration of different functions and services at one site and facilitates synergies, e.g. by joint logistic, and (iii) the modular approach which allows for a flexible combination of different types of modules adapted to requirements. In this way, the TROPOS multi-use platform system is able to integrate a full range of functions from the four TEAL sectors (Fig. 12.1) and can be perfectly adapted and used in a much greater number of global geographical locations than a non-floating, non-modular and/or a single-use platform design.

The conceptual design of the TROPOS platform involves a central unit associated with modules and satellites (TROPOS 2013b, 2015). This floating central unit can be moored to the seafloor and builds the core of the platform. The lower part of the central unit is equipped with a double hull to prevent oil spills. Modules with different functions can be directly attached to the central unit, and/or satellite units can be indirectly connected (via undersea cables), each according to requirements. Satellite units are fixed with their own mooring.

In Fig. 12.2, a schematic representation of platform elements and their functional connections is shown as an example. In this example the platform is composed of the central unit, two modules (substation and operation & maintenance base) and one type of satellite (renewable energy and fish aquaculture). Functional units are shown as black boxes, with the specific inputs and outputs relevant for their functionality (TROPOS 2014b).

The design and engineering specifications of the platform concept considers extreme weather conditions and unplanned events to be prepared for all kinds of emergencies. Safety and security of crew and visitors, and protection of the environment, are the top priority in the design of the TROPOS scenarios.

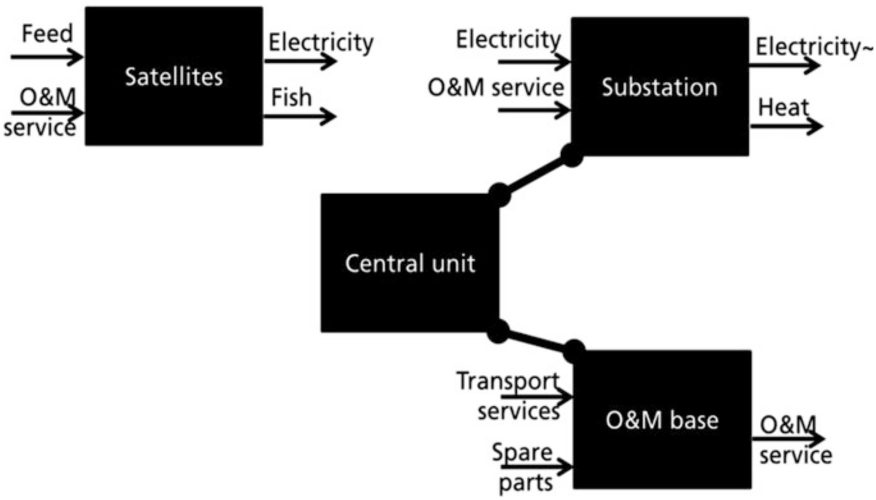

Fig. 12.2 Schematic example of TROPOS platform functional units and their connections. The example shows the main in and outputs of the satellite unit and two modules integrated into the central unit: a substation module representing the electrical connection between central unit and satellites, and an operation and maintenance (O&M) module (*Source* TROPOS 2014b)

Different concepts with different combinations of functional units from the TEAL sectors were developed in the project, among these, the so-called “*Green & Blue*” concept which is specified below.

12.2.2 The Green & Blue Concept

The Green & Blue concept is focusing on the use of physical and biological resources, intending to follow the strategies and actions of “Blue Growth[1]” as defined by the European Commission for the development of aquaculture and renewable energies in the EU. The Green & Blue concept integrates offshore aquaculture and renewable energies.

Depending on platform location and local conditions and dynamics, the renewable energy source to be harnessed might be wind, waves, solar or ocean thermal energy (Quevedo et al. 2013). Accordingly, the renewable energy component of the concept may be represented by a wind farm, wave energy converters, photovoltaic (PV) panels or an OTEC (Ocean Thermal Energy Conversion) plant.

The aquaculture component of the Green & Blue concept primarily includes fish and algae aquaculture. Generally, the fish culture unit is planned in the form of floating, submerged or drifting cages. Depending on the location, secondary cultures around the fish cages may be developed for bivalves and/or macroalgae. Additionally, if the location’s depth allows such an activity, bottom cultures could be established. The algae culture unit can include several components, e.g. production of biomass (microalgae and macroalgae), products with high market value, and biofuel/gasification from macro and microalgae, and CO_2 fixation from flue gases. Wastewater e.g. domestic wastes from a central platform can be used to nourish algae, thereby combining algae biomass production with wastewater treatment. The source for the flue gas may be emissions from the satellite or the central platform or from on-shore emission sites as CO_2-stripping at a biogas plant.

The aquaculture units (both fish and algae) take advantage of the facilities that the platform offers, namely energy, protection, anchoring and logistics with regard to installation, maintenance and operation. An example for a Green & Blue concept integrating offshore fish and algae aquaculture and wind turbines is shown in Fig. 12.3.

One Green & Blue case scenario, developed in TROPOS and designed to be located in the Mediterranean Sea in deep water locations, is described in more detail below.

[1]“Blue Growth” refers to the European Commission’s long term strategy to support sustainable growth in the marine and maritime sectors.

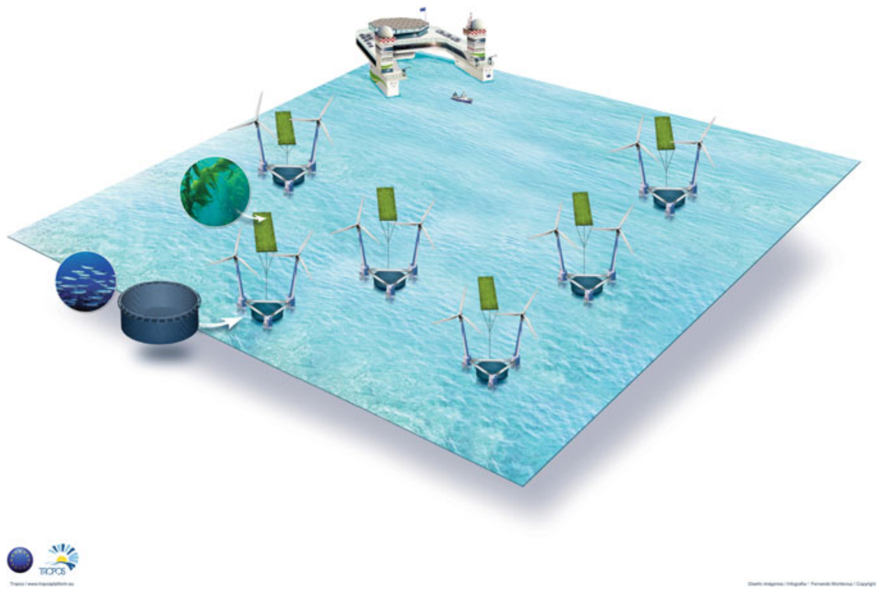

Fig. 12.3 Green & Blue concept integrating offshore fish and algae aquaculture and wind turbines (Fernando Montecruz for the TROPOS project)

12.3 The Green & Blue Concept in the Mediterranean

One Green & Blue platform was designed for a location north of Crete (southern Aegean Sea) at about 100 km distance from the shore in about 450 m water depth (Fig. 12.4). The site was chosen based on a GIS supported multi-criteria decision analysis, which also considered socio-economic and environmental aspects. Climatic, geographic and oceanographic characteristics and dynamics in this area were found to be appropriate for this platform concept (TROPOS 2013a).

In this particular scenario, fish and microalgae aquaculture are combined with wind turbines and some PV panels (see Fig. 12.3). The scenario includes six modules (integrated into the central unit) which aim to service, maintain and monitor the satellite units and to ensure smooth and optimal energy and biomass production flow. In all, there are 30 floating satellite units placed around the central unit, which comprise the wind turbines, some PV panels, as well as fish cages and algae floats.

12.3.1 Central Unit

In this concept, the central unit extends over several decks and hosts all functions and services that are needed for the daily operational requirements of the platform. This includes, among others, the engine, diesel oil tanks, waste and wastewater

Fig. 12.4 Approximate Green & Blue platform location in the Mediterranean, north of Crete (Map created by Fernando Montecruz for the TROPOS project)

storage and treatment plants, transformers, a desalination unit for freshwater production, freshwater tanks, different kind of workshops, maintenance and repair areas, air conditioning and storage rooms. Moreover the central unit hosts fire-fighting system, control, surveillance & monitoring rooms, and also offices, common and leisure rooms, laundry, kitchen and hospital (TROPOS 2014b). The energy demand of the platform will be completely met by the locally produced renewable energy; the diesel engine mainly serves as a backup in case of emergency or deficiency of the natural energy resource. Waste and wastewater produced during the operational phase of the platform will be treated following best practice and stored on board until it can be transferred to shore. Both aquaculture and energy production require specific facilities for proper operation. These facilities are organized in different modules on the central unit.

12.3.2 Modules

The major objectives of the modules integrated into the central unit in the Green & Blue concept are for monitoring, service, maintenance and processing of the energy and aquaculture production on the satellite units (TROPOS 2014a). These modules include

- The fish processing plant
- The aquaculture workshop
- The aquaculture support
- The algae biorefinery
- The substation
- Accommodation facilities

The fish processing plant provides all facilities required for processing the fish production. Generally, fish biomass produced in a farm may be either being processed on site or transported to another processing facility according to the business plan that will be followed. While for land-based or nearshore aquaculture the processing units are close to markets and the flow of product is continuous. This is not the case for offshore farms where connection with land is neither easy nor daily. Hence, an on-site processing unit is a requisite in order to prolong product's shelf life from days to weeks depending on the processing level. Also, the disadvantages of the offshore farms due to distance may turn to benefits with the production of value added products. Existing alternatives to this approach represent the use of a "boat-factory" which, however, presents some disadvantages related to dependencies on external services and the minimization of flexibilities for marketing.

In the plant, the harvested fresh fish can be directly processed without any delay. The module includes the processing facilities leading to 3 groups of products: (i) fresh fish on ice, (ii) degutted fish, subsequently IQF (Individually Quick Frozen), and (iii) processed fish (fillets or steaks) either IQF or packed in MAP (Modified Atmosphere Packaging). Special care is given to byproducts (estimated at $\sim$20% of the biomass) that are also marketed. There are cooling and freezing rooms, storages, warehouse for packaging material and an ice-production unit.

The aquaculture workshop includes a maintenance unit for repairing equipment, warehouses for storage of harvesting equipment, nets and spare parts.

The aquaculture support module includes a central communication room for control, surveillance and monitoring of the aquaculture production and environmental parameters, and for operation and control of the automated feeding system. The module also includes laboratories both for biological analysis and electronics.

In the algae biorefinery, the harvested microalgae may undergo further processing, such as extraction of proteins, lipids, carbohydrates or pigments, and conversion to biofuel.

The substation is connected to the wind farm and serves as infield cable node, voltage transformation and/or current conversion system and export cable connector between the satellite units, the central unit and the onshore grid. To establish such connection, it is necessary for the substation to have specific power transmission capabilities in combination with distinctive voltage transformation functionalities.

The accommodation module provides living space for crew and visitors.

12.3.3 Satellite Units

The Green & Blue scenario off Crete consists of 30 floating triangular satellite units. Each semi-submersible satellite unit is equipped with two 3.5 MW wind turbines (Fig. 12.5). Some units also include small 434 kW PV panels. The wind turbines have a rotor diameter of 112 m and total production of all 60 turbines (2 per satellite unit) was estimated with about 198 MW (TROPOS 2013c).

According to the design, 30 units will be installed allowing a maximum production capacity of 750 t fish per week. In each unit an open sea surface cage is integrated at the inert part of the triangular base (Figs. 12.4 and 12.6). All daily operational equipment including feed distributor, feed storage silos (66 t, 100 m^3) and monitoring equipment are incorporated to the base, and are remotely controlled from the central platform. For the Green & Blue platform in the Mediterranean, the production plan includes the rearing of 3 different species in two-year rearing cycles: (i) the European Sea Bass (*Dicentrarchus labrax*), (ii) the Meagre (*Argyrosomus regius*), and (iii) the Greater Amberjack (*Seriola dumerili*).

The cage is a typical cylindrical floating offshore cage of 33/36 m (internal/external) diameter. The volume contained in the net cage is about 25,000 m^3. In some of the units, the top of the fish cage is covered by solar panels for additional energy production (TROPOS 2013c).

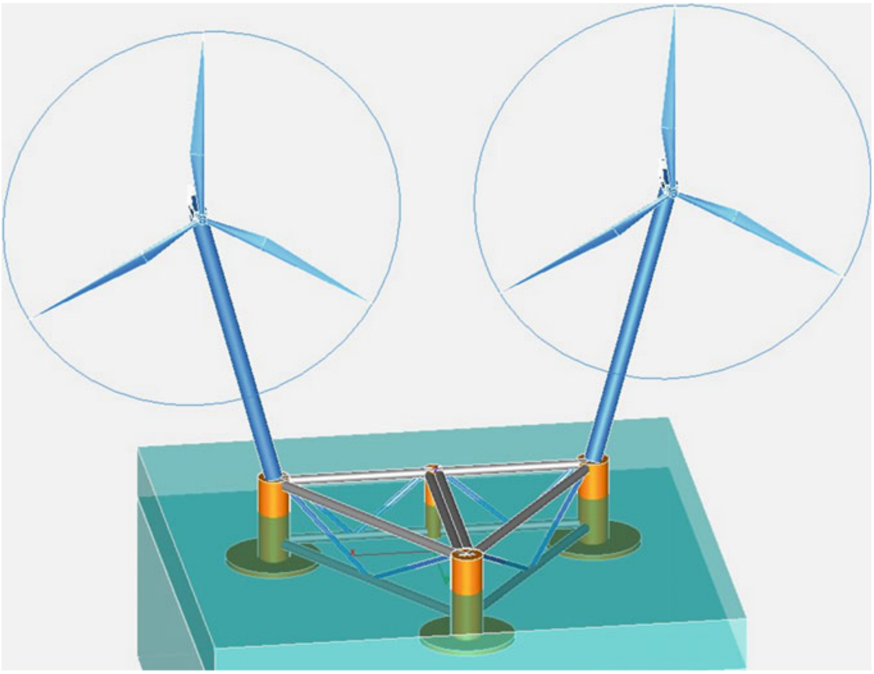

Fig. 12.5 3D view of a floating wind satellite unit designed by EnerOcean S.L. for the TROPOS Green & Blue concept based on W2Power patented design (*Source* TROPOS 2013c)

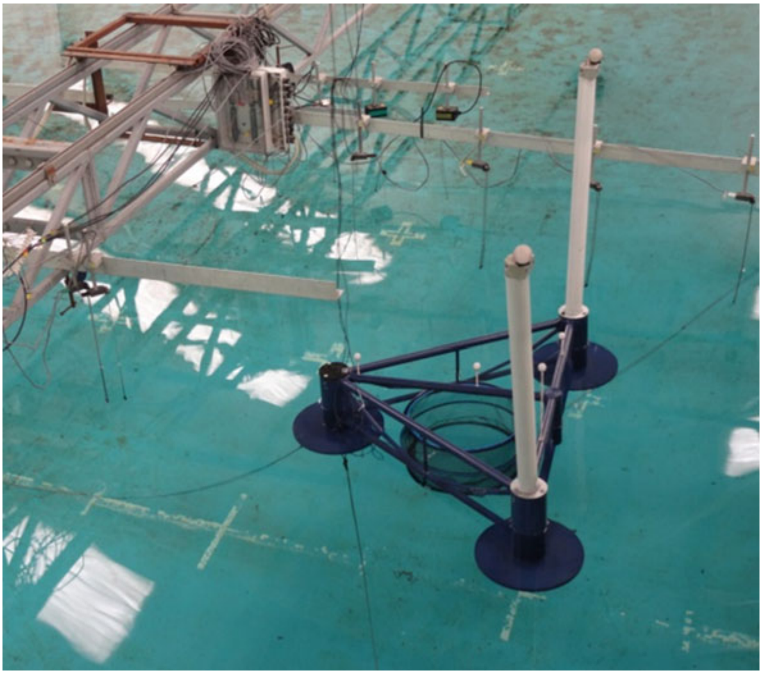

Fig. 12.6 A model of the Green & Blue satellite unit triangular base structure with the fish net cage inside; the model was tested at the UCC-BEAUFORT (HMRC)—National Ocean Wave Basin in Cork (Ireland), model scale 1:100 (*Source* TROPOS 2014c)

The microalgae production unit or float containing the microalgae cultures is connected to the triangular construction, one float per satellite unit, making a total of 30 algae floats (Fig. 12.3). These photo-bioreactors are a closed system. The dimensions of a float are 50 × 200 m with an inserted phytoplankton unit of 400 m^3. Two thrusters, located at the end of the plant, help to manoeuvre the submersible culture system (Fig. 12.7).

The satellite units are unmanned and monitored, operated and controlled from the central unit. The fish cages and the algae photo-bioreactors are equipped with sensors for online control and monitoring from the aquaculture modules.

Energy demands of the sensors as well as of the automated fish feeding system are met by the local production from wind and/or solar energy. Service and maintenance are provided by a crew based on the central unit.

In summary, the final layout of the satellite is comprised of:

- Two turbines (3.5 MW each/90 m height) installed on a triangular shaped platform (column distance (base) 90 m/column distance (triangle legs) 80 m) and their auxiliary component to enable an appropriate grid connection.
- A cage for aquaculture moored between the triangular legs (25,000 m^3/diameter 33 m/depth 30 m).

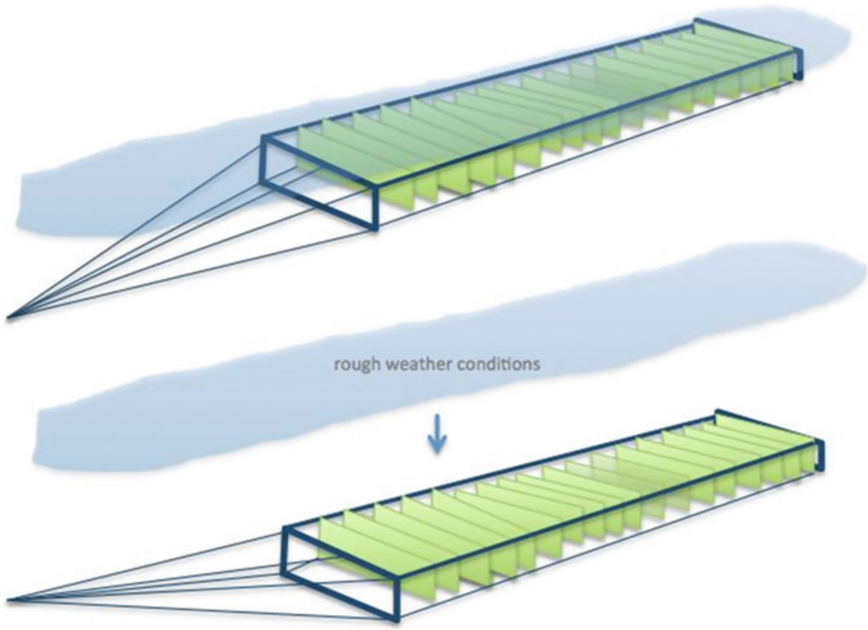

Fig. 12.7 Algae aquaculture part of the Green & Blue satellite unit; the submersible algae float is equipped with two thrusters (*Source* TROPOS 2014c)

- An Algae Production Unit connected to the wind satellite unit at a single point.
- An automatic feeding system (64 t in two silos with two different feeds and a distribution system located on the “vertical columns” of the triangle).
- An automatic feeding system for algae production (50 t CO_2 storage + nutrients).
- PV panels are installed on the top of the module for an additive 0.5 MW per satellite

12.3.4 Aquaculture Production Flow

Based on a theoretical production analysis the total aquaculture yield in the Green & Blue scenario in the Mediterranean is estimated to be 7,000 t of fish in a biannual production cycle and 2,000 t of algae in continuous production.

12.3.4.1 Finfish Aquaculture

The fish production plan developed for this Green & Blue scenario involves the rearing of three different species in a two-year rearing cycles. Taking advantage of the different natural spawning period of the selected species and in order to avoid an overlap in harvesting, stocking of cages is performed annually with half of the dedicated cages for each species as follows:

- European sea bass (*Dicentrarchus labrax*) a total of 8 cages; stocking 1 cage per month in February, March, April and May every year;
- Greater amberjack (*Seriola dumerili*) a total of 10 cages; stocking 5 cages in July every year;
- Meagre (*Argyrosomus regius*) a total of 10 cages; stocking five cages in October every year.

The 2 remaining fish cages serve as backup units. The stocking with fry will be followed by a rearing period of 2 years until market-size is reached (European sea bass 0.6 kg, greater amberjack 3 kg, meagre 2.5 kg). Fish will be fed with artificial feeds delivered by the automated feeding system. The amount of feed is based on the demand. Feeds will be transferred from cargo boats directly to the satellites and the silos will be loaded monthly.

Fish harvesting from the cages will be performed with a fish-pump mounted on a working barge and the harvested biomass will be transported to the central unit. The same fish-pump is used to upload the fish to the aquaculture module on the central platform (TROPOS 2013c).

In Table 12.1 the results of a production analysis performed on a monthly basis are shown. For all three fish species the amount of required feed, energy, ice for

Table 12.1 Production analysis (input/output table) of the complete Green & Blue fish aquaculture farm in the Mediterranean

	Species	Fish fry (1000 ind.)	Feeds (t)	Energy (kWh)	Ice (t)	Harvested fish (1000 ind.)	Harvested biomass (t)
January	European seabass	641	735	145,306	152	507	304
February		641	774	134,536	152	507	304
March		641	807	145,156	152	507	304
April		641	829	141,316	152	507	304
May	Greater amberjack		819	146,138	256	342	512
June		410	748	142,736	292	195	584
July		410	717	146,276	292	195	584
August		205	745	144,808	146	97	292
September	Meagre		763	142,598	256	427	512
October		513	706	146,372	304	243	608
November		513	657	142,832	304	243	608
December		256	678	144,856	152	122	304
Total		**4873**	**8980**	**1,722,930**	**2610**	**3892**	**5220**
Monthly average (t)		487	748	143,578	218	324	435

Source (TROPOS 2014b)

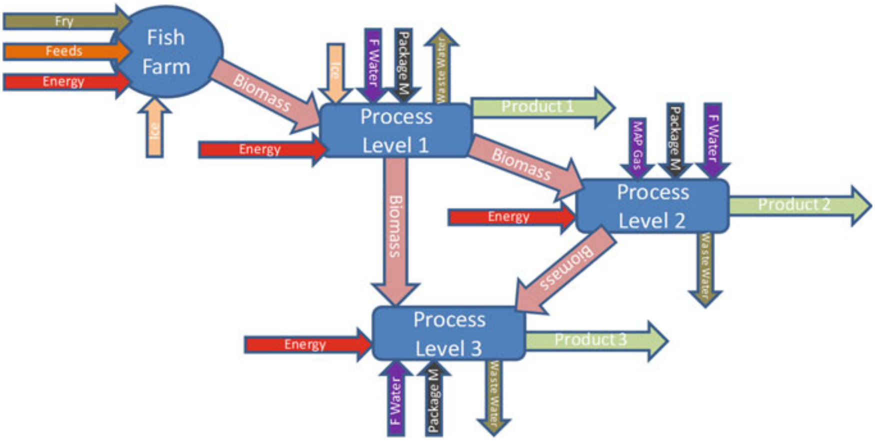

Fig. 12.8 Fish aquaculture and processing plant flow chart including all inputs and outputs in the Green & Blue concept (*Source* TROPOS 2014b)

conservation of the final product, and the number and total biomass of harvested fish was calculated.

After harvesting, the fish biomass processing in the processing module is organized in 3 levels (Fig. 12.8):

- Process Level 1, Basic Processing—in this step fish are processed after harvest either as fresh product (product 1) or pretreated for further processing in process levels 2 or 3.
- Process Level 2, Filet Processing and Modified Atmosphere Packaging—in this step fish are processed to produce filets and other products that require packaging in a modified atmosphere.
- Process Level 3, IQF (Individually Quick Frozen) Processing—in this step the final product is frozen biomass. Biomass inputs to this process level 3 are whole fish from process level 1 and filet from process level 2.

The outputs from levels 2 and 3, apart from the final product include a significant amount of byproducts, which are not considered waste but as a primary material for other industries (e.g. fish meal production). Therefore, all byproducts are refrigerated and exported (TROPOS 2014b).

In terms of biomass, the total products from the Green & Blue fish aquaculture are about 25% fresh fish, 55% transformed (Individually Quick Freezing/Modified Atmosphere Product), 20% byproducts.

All the energy required for the operation of the fish aquaculture in the Green & Blue scenario will be provided by the local renewable energy production.

12.3.4.2 Microalgae Aquaculture

The algae production starts with the seeding of a microalgae starter-culture in the closed photo-bioreactors on the algae floats. The key parameters for the algae production are irradiance, nutrients and size of installation. As the microalgae are in a closed system, the medium will be supplemented with some nutrients, such as nitrogen (9 t/year), phosphorus and micronutrients (1.5 t/year) (Table 12.2). CO_2 is also applied to enhance the production yield. This will be done by direct injection from a 50 t cryogenic CO_2 storage with assistance of an air blower.

The online control system allows monitoring and controlling of the production process inside the photo-bioreactors from board of the central unit. The unit is operating valves and pumps and measures, among other parameters, temperature, the pH value and the optical density in the system continuously. Environmental ambient parameters like irradiance and temperature are also recorded.

When the microalgae culture reaches the desired concentration the culture is harvested. The actual harvesting step of algae from the photo-bioreactors is carried out on the satellite and the biomass is then shuttled to the central platform for storage and further downstreaming. A two-step algae harvest is implemented with a first step consisting in a pre-concentration of the algae suspension followed by a second step of centrifugation. The dewatered algae biomass is then dried by spray-dryer or solar-dryer and either cold stored until transport to the shore or

Table 12.2 Details on the algae aquaculture production unit, including dimension of floats, inputs in terms of nutrients and output in terms of production as calculated based on a production analysis

Algae aquaculture				
Component	Subsystem		Number	Units
Units	Number of units		30	
	Dimension	Length	200	m
		Beam	50	m
		Area	10,000	m²
	Production per unit		65	t/a
	Total production (6–8 months, 30 units)		1950	t/a
Store nutrients	Nitrogen consumption per unit		9.0	t/a
	Phosphorus and micronutrients consumption per unit		1.5	t/a
	Volume per unit (Phytoplant)		400	m³
Production capacity	Max. production per week		750	t
	Production per day		300	t

Source (TROPOS 2013c)

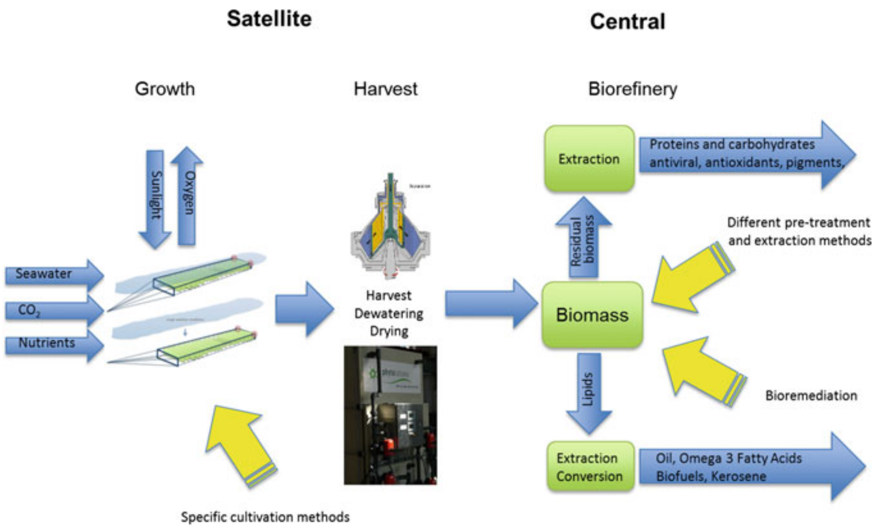

Fig. 12.9 Algae aquaculture production and processing; flow chart including all inputs and outputs in the Green & Blue concept (© by Phytolutions)

Table 12.3 Estimated microalgae production per month considering all 30 satellites units of the Green & Blue scenario

Months	Product (t)
Jan	60
Feb	80
Mar	130
Apr	150
May	200
Jun	280
Jul	290
Aug	250
Sep	210
Oct	160
Nov	80
Dec	60
Estimate per year	1950

Source (TROPOS 2014b)

directly further processed in the algae biorefinery module on the central platform. A flow model of the entire algae aquaculture production and processing is shown in Fig. 12.9.

In total, considering all 30 satellite units of the Green & Blue scenario, the annual production capacity of the facility was estimated with 1950 t/year (dry weight) (Tables 12.2 and 12.3).

Analysis of the economic impact confirmed that the Green & Blue concept in the Mediterranean has a strong economic case for development (TROPOS 2014d) and a virtual environmental impact assessment showed that the concept has minimal negative environmental impact (TROPOS 2014e).

12.4 Summary

Moving offshore involves a lot of advantages such as reduced competition with other activities compared to the near shore zone, optimum culture conditions in term of water quality and absence of pathogens, and rapid dispersal and dilution of any effluents to the wide open ocean (i.e. less negative impact on the environment; Lu et al. 2014). Moving offshore, however, also goes along with a major challenge, namely the suitable technology. Weather and wave conditions are often harsh in the open ocean and deep waters make the fixation of aquaculture facilities a difficult task. Moreover, the distance to the coast significantly complicates logistic service and supply, and operation and maintenance. A solution to overcome these problems and obstacles is represented by the TROPOS multi-use platform approach. The floating structure was especially designed for offshore conditions and allows for use in deep waters. As the annual offshore wind energy capacity will experience an average net increase of 21.5% every year until 2020, the combination of marine aquaculture farming with offshore wind energy exploitation seems obvious. The Green & Blue concept intends to integrate an offshore wind farm with aquaculture facilities for fish and algae, so as to create synergies among the activities: (i) Since many components of the system need energy (e.g. workshop, laboratory, feeding unit, etc.), aquaculture can achieve high levels of autonomy when combined with the wind turbines triggering the development of the offshore aquaculture further; (ii) Placing the cages between the turbines will save space and mooring lines; (iii) Since maintenance tasks have to be provided in a frequent basis for both fish and wind farm, the service infrastructure can be shared; (iv) Based on this, having a common accommodation unit on the platform, downtime periods will be decreased for both industries (since there will be permanently located personnel providing continuous inspections and routine maintenance tasks, and able to respond fast in case needed). Apart from this, sharing of divers and diving infrastructure, logistics, maintenance tools, workshops, environmental monitoring, etc. will reduce the service/maintenance costs.

12.5 Outlook

Multi-purpose offshore platforms are designed to incorporate modules of several compatible activities, and thus, provides the opportunity for the aquaculture industry to operate viably and profitably in offshore sites. Since mooring is one of the major constrains for offshore aquaculture (the industry operates in depth <100 m), the synergy with the platform is vital for a feasible industry at deep offshore sites. The innovative synergies developed on modular multi-purpose platforms provide the opportunity for aquaculture to expand in offshore sites and meet future demands. Important constraints for success are the co-development and shared use of infrastructure, the selection of sites and technologies appropriate for environmental conditions, and the synergies in operational planning.

Until now, the aquaculture industry has moved offshore slowly and conservatively due to high costs and immaturity of innovative technologies. Some prototypes, consisting of submersible or semi-submersible cages, are currently available, allowing farms to be located farther from the coast than today. However, a significant research effort is needed on the development of new culture technologies as, although several prototypes have been proposed, few have been tested in commercial scale.

With its innovative design and technology the TROPOS concept represents an advanced solution for an integrated and synergistic offshore multi-use approach involving aquaculture and microalgae production. However, the next essential step is to move from theoretical approaches and modelled designs towards "real world" deployments. Even if financial support is possibly required at the beginning, pilot scale deployments are vital to proceed in the field of multi-use offshore installations.

References

Cressey, D. (2009). Aquaculture: Future fish. *Nature, 458,* 398–400.

Enzing, C., Ploeg, M., Barbosa, M., & Sijtsma, I. (2014). *Microalgae-based products for the food and feed sector: An outlook for Europe*. JRC Scientific and Policy Reports, Luxembourg: Publications Office of the European Union.

FAO. (2014). *The state of world fisheries and aquaculture*. Rome: Food and Agriculture Organization of the United Nations.

Lu, S. Y., Jason, C. S., Wesnigk, J., Delory, E., Quevedo, E., Hernández, J., et al. (2014). Environmental aspects of designing multi-purpose offshore platforms in the scope of the FP7 TROPOS Project. *Paper presented at the OCEANS 14 MTS/IEEE*, Taipei, Taiwan.

Muller-Feuga, A. (2004). Microalgae for aquaculture: The current global situation and future trends. In A. Richmond (Ed.), *Handbook of microalgal culture* (pp. 352–364). Oxford: Blackwell Science.

Papandroulakis, N., Anastasiadis, P., Thomsen, C., Koutandos, E., Mayorga, P., Quevedo, E. et al. (2014). Modular multipurpose offshore platforms: Innovative opportunities for aquaculture. In *Book of abstracts* (pp. 955–956) European Aquaculture Society Special Publication.

Quevedo, E., Delory, E., Castro, A., Llinás, O. & Hernández, J. (2012, October). Modular multi-purpose offshore platforms, the TROPOS project approach. In *Paper presented at the 4th International Conference on Ocean Energy*, Dublin.

Quevedo, E., Cartón, M., Delory, E., Castro, A., Hernández, J., Llinás, O., et al. (2013, June). Multi-use offshore platform configurations in the scope of the FP7 TROPOS Project. In *Paper presented at the OCEANS 13 MTS/IEEE*, Bergen.

Ryan, J. (2004). Farming the deep blue. In G. Mills & D. Maguire (Eds.), Dublin: Bord Iascaugh Mhara—Irish Sea Fisheries Board (BIM) & Irish Marine Institute. Retrieved from http://www.bim.ie/media/bim/content/downloads/FarmingtheDeepBlue.pdf

Ryan, J., Jackson, D., & Maguire, D. (contributing authors) (2007). Offshore aquaculture development in Ireland; next steps. In: L. Watson, A. Drumm (Eds.), *Technical report jointly commissioned by Bord Iascaugh Mhara—Irish Sea Fisheries Board (BIM) & Irish Marine Institute*, p. 35.

Spolaore, P., Joannis-Cassan, C., Duran, E., & Isambert, A. (2006). Commercial applications of microalgae. *Journal of Biosciences and Bioengineering, 101,* 86–96.

TROPOS (2013a). D2.3—Sample locations and setups for further design. Retrieved from www.tropospIatform.eu

TROPOS (2013b). D3.2—Technical concept dossier for the central unit. Retrieved from www.tropospIatform.eu

TROPOS (2013c). D3.4—Technical concept dossier for the satellite unit. Retrieved from www.tropospIatform.eu

TROPOS (2014a). D3.3—Technical dossier for each of the established modules including key features. Retrieved from www.tropospIatform.eu

TROPOS (2014b). D3.5—Integrated concept offshore platform system design. Retrieved from www.tropospIatform.eu

TROPOS (2014c). D4.1—Report on hydrodynamic simulations of platform models and model validation. Retrieved from www.tropospIatform.eu

TROPOS (2014d). D5.2—An assessment of the economic impact, on local and regional economics, of the large scale deployment. Retrieved from www.tropospIatform.eu

TROPOS (2014e). D6.2—Report on environmental impact assessment and mitigation strategies. Retrieved from www.tropospIatform.eu

TROPOS (2015). D4.3—Complete design specifications of 3 reference TROPOS systems. Retrieved from www.tropospIatform.eu

Chapter 13
Offshore Platforms and Mariculture in the US

Jeffrey B. Kaiser and Michael D. Chambers

Abstract Global demand for seafood is increasing. Supply from wild caught sources has been essentially flat for twenty years and, depending on the specific fishery, in decline for many species that are considered fully exploited or over-exploited. As the fastest growing sector of world food production, aquaculture is increasingly playing a major role and currently accounts for nearly half of the total aquatic production worldwide. Marine cage culture in particular provides an opportunity to utilize vast amounts of the world's surface area to produce fish, shellfish, and plants, while avoiding land-use conflicts in crowded coastal regions. Currently in the US, very small volumes of marine fish are produced and very large volumes are imported. This trend shows no signs of slowing down with an ever increasing annual seafood trade deficit. In an effort to initiate more domestic production, private companies, research institutions, and government agencies have all been involved in various types of aquaculture production. Aquaculture can be generally categorized as land-based, near shore, or offshore. Offshore marine fish culture utilizing cages has been conducted on both the east and west coast of the US as well as in the Gulf of Mexico (GoM). Specifics on the projects in the GoM are described in the following sections.

13.1 Background

The world's population is estimated to be approaching 9 billion people by 2050. UN estimates project the total global food supply will need to increase by 70% to keep up with demand and the growth of a larger and more urban population

J.B. Kaiser (✉)
Marine Science Institute's Fisheries and Mariculture Laboratory,
The University of Texas at Austin, Port Aransas, TX, USA
e-mail: jeff.kaiser@utexas.edu

M.D. Chambers
School of Marine Science and Ocean Engineering,
University of New Hampshire, Morse Hall, Room 164, Durham, NH, USA

B.H. Buck and R. Langan (eds.), *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, DOI 10.1007/978-3-319-51159-7_13

(FAO 2009). The world's oceans cover over 70% of the earth's surface and provide a large area to situate aquaculture operations that produce marine fish, shellfish, and plants. Currently, the ocean is underutilized as a location for protein production with 5% of the global protein supply (Oceanworld 2014) and a mere 2% of the total human calorie intake (UNEP 2012) acquired from this biome. Demand for food combined with a shortage of new arable land will require the global population to attempt to maximize production from the world's oceans. Potable freshwater and its distribution and use in the future is another critical reason to utilize the marine environment for aquaculture (Famiglietti 2014). All living organisms must have freshwater to live, including humans. The efficiency of rearing a million tons of protein in the marine environment when compared to producing the same amount of terrestrial protein becomes evident when the freshwater demand is considered. The current composition and location of water on the earth makes an obvious case for the use of the marine environment for aquaculture—that is where the water is! (Fig. 13.1).

The world is embracing aquaculture. Global output has increased from 7 million tons in 1980 to nearly 70 million tons currently and cultured product volume is projected to overtake capture fisheries within a few years. The US on the other hand, while being a major consumer of seafood products (ranked second behind

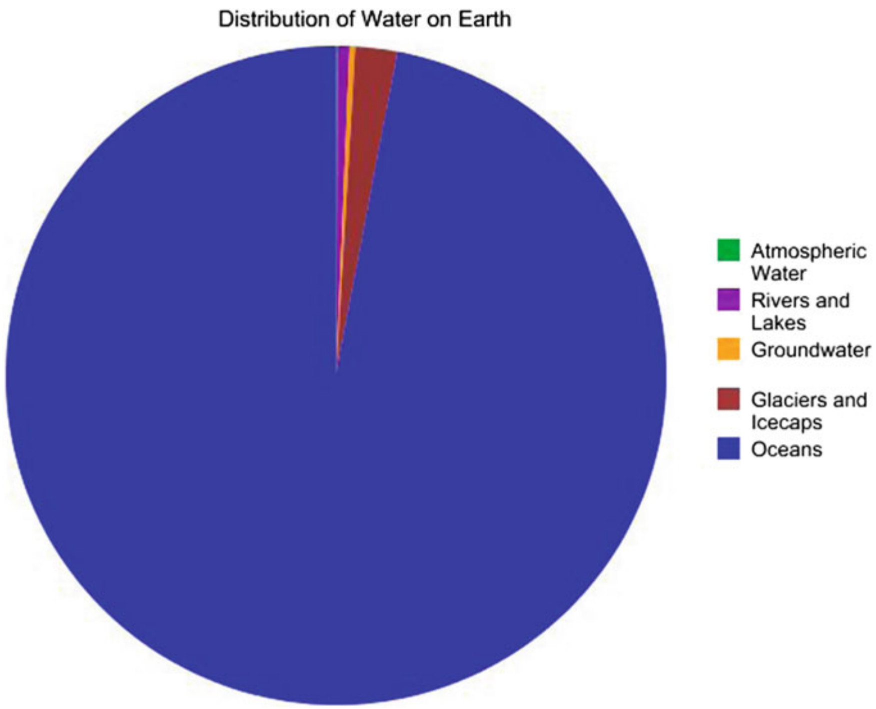

Fig. 13.1 Distribution of the earth's water (*Image* SanibelSeaschool.org)

China), is a minor producer of product and barely ranks in the top 15 producing countries (FAOFishStat 2016). The US currently imports around 90% of its edible seafood supply and has an annual trade deficit value of more than $10 billion—and that number is increasing each year. Ironically, for a country that has not effectively promoted domestic aquaculture expansion through easing of regulations and permitting processes, it is estimated that half of the product the US imports each year is produced by aquaculture (NOAA FishWatch.gov 2014).

Nearly half of the global population currently lives within 200 km of a coastline and that figure is expected to double by 2025 (PRB 2003). User conflicts and land demands for development will compete for space to conduct commercial scale marine aquaculture utilizing land-based pond or tank systems. Increasingly, both researchers and investors are considering the benefits of moving into the offshore environment where both water volume and water quality ameliorate many of the issues faced by traditional aquaculture production (Price and Morris 2013). While typically considered near shore, the explosion of the 1.8 million ton/yr salmon culture industry in the last 30 years is just one example of the potential rearing organisms in the marine environment offers. The vast majority of cage or net-pen operations currently in place are next to or within sight of land, which in most cases locates them within 10 miles of shore. Most, therefore, are situated with some sort of land mass nearby and are not exposed on all sides to prevailing wind and sea conditions.

With regards to the US coastline, several factors for siting of offshore aquaculture projects must be taken into consideration such as: distance from shore, water depth, logistics of maintaining personnel, feed, and equipment, transportation issues, environmental impact, culture species availability, product markets, among others. The GoM presents a unique situation because it is a sub-tropical saltwater environment which currently has nearly 3000 platforms in place associated with energy production. Certainly not all of these structures are in suitable locations for siting projects, but when the aforementioned factors are considered several of the existing platforms would be candidates for aquaculture. Supporting the energy industry are numerous vessels, terminal facilities, heavy equipment and experienced personnel, all of which would be valuable assets for the development of a commercial aquaculture venture in the offshore environment.

The mariculture projects utilizing offshore platforms described in the following sections were conducted in totally exposed locations and as such, presented the operators with unique challenges. Since 1990, there have only been three projects in GoM waters attempting to raise fish in cages either nearby or attached to oil and gas platforms. The platforms were used for monitoring the cage systems in addition to being a base of operation in two cases and strictly for observation purposes during the third project. It is important for the reader to note that the perspective offered by the co-authors is from direct personal experience working on two of these projects over several years—installing cage systems, stocking and feeding fish, inspecting and maintaining the cages, and living or working on the platforms involved. Results of these efforts will be discussed along with considerations for future use of oil and gas platforms for offshore aquaculture.

13.2 The Gulf of Mexico

Location is arguably the most important factor for any offshore cage culture project. Siting will dictate the expected sea conditions, type of cage system utilized, water parameters, and all transportation and logistical planning. These factors, among others, will ultimately determine the success or failure of a project. The GoM is characterized by short period wind driven waves for much of the year combined with tremendously powerful episodic tropical events during the June–November hurricane season. Offshore platforms, while engineered to withstand tremendous forces for decades, can be damaged or destroyed during hurricanes and tropical storms (Fig. 13.2) and an aquaculture project needs to have worst case contingency plans in place. Cage systems at totally exposed locations should be designed to survive a tropical event with nominal damage and above all, retain the fish within the system. Escaping the energy at the ocean surface is critical and submergible or submerged cages will likely be the preferred system in the GoM.

The distance the continental shelf extends into the GoM varies greatly depending on the specific location. It is the authors' assertion based on cage designs and diving requirements that for the purposes of siting, water depths of 30–60 + m would be considered adequate for offshore cage culture systems. This depth would allow for a cage to be submerged 10 m to escape the high energy surface forces and still have enough space for the cage volume and some allowance to maintain the system off of the bottom. The locations of the two projects off the coast of Texas, one 10 km

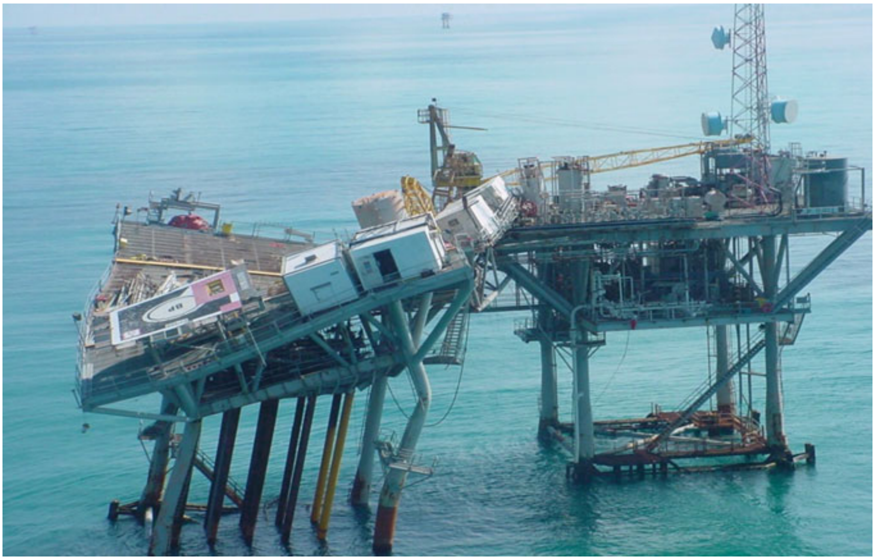

Fig. 13.2 Offshore platform damaged during a hurricane off of Louisiana

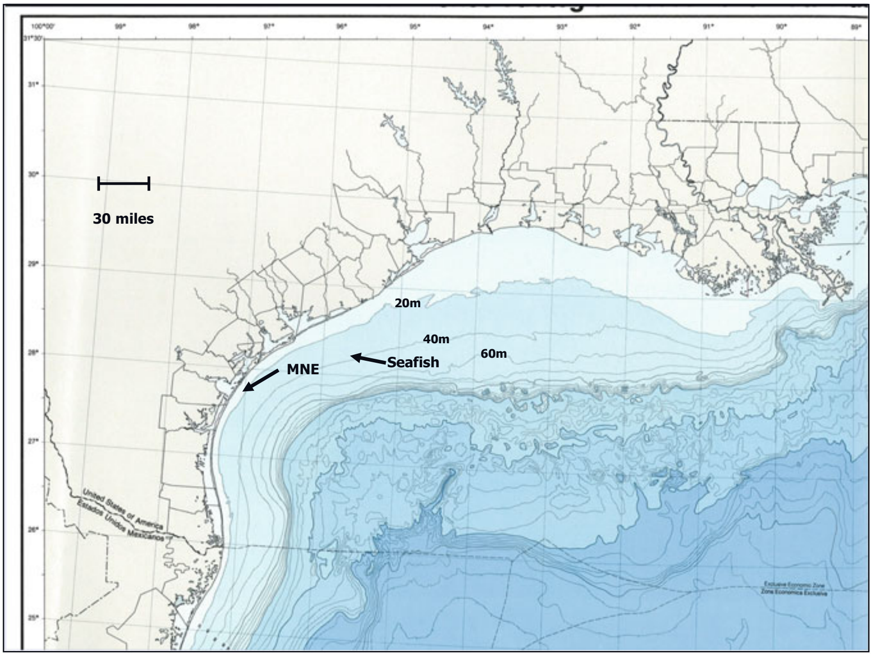

Fig. 13.3 Site locations for MNE Inc and Seafish aquaculture projects in the Gulf of Mexico

(21 m deep) and the other 42 km (40 m deep) offshore, are designated in Fig. 13.3. Conditions during these particular projects were seas calm to 7+ m, winds calm to above hurricane strength (78 knots and then the anemometer disappeared), and currents 0 to an estimated 130 cm/sec or 2.5 knots. During the course of several years, the weather pattern observed from worst to best conditions during seasons was periodic tropical events, followed by spring, winter, fall and summer. The period from February to May is particularly damaging to cage systems since the wind velocity and subsequent sea state often prevent site visits for maintenance from several days to as much as 2 weeks.

Wave action, currents, and fouling of net or cage materials will constantly wear and ultimately test all the materials of any offshore aquaculture system. Since weather and sea state determines when components can be safely inspected and repaired, the chosen design must assume extended maintenance intervals from days to even weeks in extreme conditions. Unfortunately, in several instances this inability to address a problem immediately, as can often be with onshore or near-shore systems, has proven to be the greatest challenge in the GoM. Personnel simply cannot safely operate in heavy seas and once a net, stanchion, mooring rope or chain, or any other part of the cage is compromised, waiting for the weather to subside is the only option. Frequently this means that what begins as a minor issue, combined with adverse conditions over several days, eventually causes major damage and there is absolutely nothing on-site personnel can do to prevent it. In some cases main component issues such as mooring failures or broken structural pieces will not result in a permanent setback to a project. Other situations, however, such as gaping holes in netting, cages breaking free and going adrift/sinking, or catastrophic failure of an entire cage system present an entirely different set of circumstances. The offshore environment is extremely challenging and it should be noted that every project in the GoM to date has had one or several of these events occur, often simultaneously.

In addition to the high energy environment of the GoM, another serious issue with netting and other containment materials is biofouling. The wave and current forces exerted on the cage systems stress the components and as barnacles, hydroids, and other organisms accumulate this stress increases. Antifouling paint and other coatings are available and were applied to cage materials however these are meant to reduce biofouling and are not capable of eliminating it altogether. Each year during the spring and early summer the GoM waters begin to warm and a significant amount of fouling occurred very quickly on the cage systems. The only options available are to either clean a cage in place or replace components when the accumulation becomes severe. Needless to say, the challenge of changing a 30–40 m diameter net that weighs several tons in the offshore GoM environment resulted in the cleaning option being employed. Figure 13.4 shows the preventative effect of copper based antifoulant paint on fiberglass panels on the left, with the top row being the treated samples. On the right the drag created by a virtual carpet of hydroids is seen on cage netting in a strong current. In addition to creating additional stress on all the system components, the deformation of much of the netting also effectively reduced the cage volume significantly. Any future offshore projects in the Gulf, however, will have to seriously consider biofouling and how to prevent and adequately deal with the inevitable growth of numerous marine organisms, particularly on the netting or containment materials.

Logistically speaking, operating at exposed locations offshore is significantly more expensive than onshore and near shore sites, largely due to transportation costs. Personnel, cage systems, maintenance equipment, fish, and feed are some of items that have to be transported by either air or sea to the project site whether the platform involved is manned or unmanned. Both platform situations have been tried during the GoM projects and each had its advantages as well as disadvantages. Certainly having a large, stable structure with multiple decks, living quarters, a power supply and crane in an otherwise uninhabitable offshore environment is an asset to an aquaculture venture. In the two projects off the coast of Texas, cages were either attached directly to the legs of a platform or mooring lines from the system were connected to the structure(s) at various points as shown in Fig. 13.5.

Fig. 13.4 *Top* Antifouling effect of copper based paint (*top row* are treated samples). *Bottom* virtual carpet of hydroids on cage netting

13.3 Past Projects

The history of mariculture utilizing offshore platforms in US waters begins in 1990 off the coast of Texas (Chambers 1998; Kaiser 2003). During the next five years MNE, a wholly owned subsidiary of Occidental Petroleum, embarked on a project to assess the feasibility of using oil and gas platforms as a base of operations for fish production. These included both manned and unmanned structures located 11–54 km offshore at depths of 20–80 m in both state and federal waters. Several cage designs were deployed, including both surface and submerged systems all of which were connected at some point to the platform itself. Various types of feed units were designed and placed on the platforms and company biologists would visit the projects sites every 1–2 weeks to inspect the cages and fish, re-supply the feeders, and perform general maintenance wherever required.

Red drum *Sciaenops ocellatus* was the primary species used during the project although on one occasion a smaller prototype cage was stocked with Florida pompano *Trachinotus carolinus*. Red drum from 30–85 g were acquired and transported to the project sites utilizing offshore crew boats in a fiberglass holding tank with supplemental pure oxygen. Stress and subsequent mortality was a

Fig. 13.5 Dunlop Tempest 4™ 18,000 m^3 cage system in 40 m of water at the platform site 54 km offshore on the central coast of Texas

challenge and it was not uncommon to experience losses of 25% or more during the transport depending on a number of factors. Once in the cage and after commencing feeding however, the fish exhibited very good overall health and no incidence of disease or parasitic outbreaks were observed. Grow out of red drum for 6–12 months to a market size of 0.7–1.0 kg at final harvest densities of 7–40 kg/m^3 was successful on three occasions totaling approximately 7300 kg (Chambers 1998). Though not a significant amount of production in terms of commercial volumes, this project stands alone as the only example of fish successfully stocked, fed, and harvested offshore in the Gulf of Mexico to date (Fig. 13.6).

The cages that survived the extreme GoM conditions during the course of the project were smaller, submerged designs whose cost per cubic meter would make them uneconomical for a large scale operation. Results of the MNE project demonstrated that the fish growth and acclimation to the cage system were very good and maintaining them from a biological standpoint was not particularly difficult. The maintenance of cage system components on the other hand, combined with the logistics of supplying feed and the production costs of simply operating offshore resulted in the shutdown of the project in 1995.

The next project along the Texas coast was a joint venture with Shell Oil company called Seafish Mariculture which took place from 1997–1999 (Kaiser 2003). The site chosen for the cages was an active platform complex 54 km offshore of the middle Texas coast in 40 m of water. This project differed from MNE in that it was the first commercial scale cage installation effort with biologists living

Fig. 13.6 A portion of the 1.0 kg red drum harvest during the MNE/Occidental project in 1995

on the platform full time to monitor and maintain the systems. Two person crews alternated during a 7 day on, 7 day off schedule which was coordinated with planned helicopter transport of platform personnel to minimize costs. Cage system supplies, fish food, fuel, water, and anything else needed for the project was delivered by crew boats out of Galveston, Texas and also coordinated with previously scheduled trips to increase efficiency. The platform was outfitted with permanent living quarters, a 7.3 m service vessel that could be craned off the platform, and a pneumatic Akva automated feed system with hoppers that held several tons of fish feed.

The cages that were tried during the project were both systems used in the salmon industry consisting of a circular or hexagonal floating collar portion, stanchions along the circumference, and a 30–40 m diameter cage with a weighted net portion approximately 15 m deep. The first system was similar to many currently used around the world and was constructed entirely of high density polyethylene (HDPE) and featured a double collar ring at the surface. The cage was constructed onshore at a terminal in Galveston and then towed to the site, moored, and had the main net installed along with an interior nursery cage to allow transport of smaller fish to the site (Fig. 13.7).

The system was situated between two platforms with half of the eight mooring lines connected to the legs of the structures and the other half anchored several hundred yards away with concrete blocks and anchors common to the aquaculture industry. Initially, the system performed adequately and was compliant enough to absorb the daily equipment stress as well as the periodic heavy seas that characterize the Gulf (Fig. 13.8).

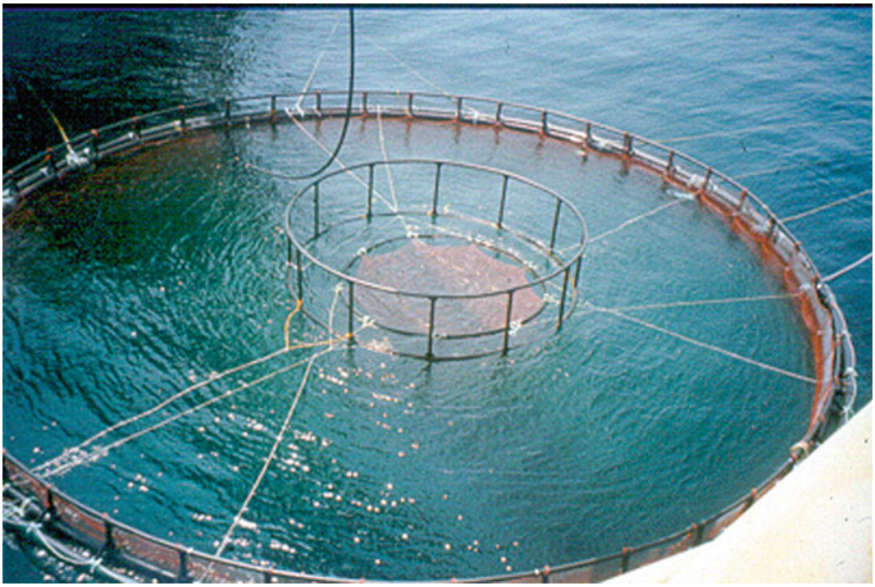

Fig. 13.7 10,000 m^3 double ring HDPE 30 m diameter net pen moored between two platforms off of the central Texas coast

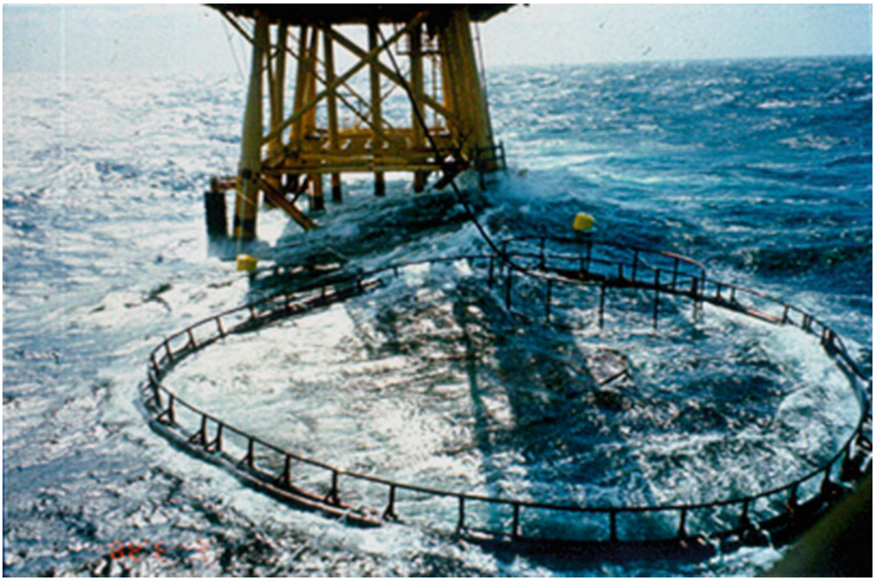

Fig. 13.8 Typical 4–5 m winter seas moving through the cage and platform site

While HDPE is a strong and versatile material used globally in numerous cage culture applications, the high energy surface action in the GoM exerted forces on the cage which eventually began to break various components, especially the stanchions and polysteel rope connections to the top of the net. This damage combined with a particularly active tropical season during 1998 proved to be too much and the system was totally destroyed by a storm and several thousand red drum were lost in the process.

The next system deployed was an 18,000 m^3 Dunlop Tempest™ cage system consisting of 0.4 m diameter 16 m long pressurized rubber hose sections connected by metal flanges at each juncture of the octagonal structure. This cage was located 100 yards from the platforms and attached to the legs of the structures in addition to mooring lines spread in different directions with concrete blocks and anchors (Fig. 13.9). Designed for use at very exposed offshore locations, the cage was extremely strong and the floating collar portion in particular was able to withstand tremendous forces during the project. As is the case in most cage culture operations however, the netting can become easily compromised for a variety of reasons and a significant amount of time was spent in the water patching holes as well as cleaning biofouling on the net. Staying ahead of the maintenance required on a large system proved problematic during the project and it was a constant challenge for personnel

Fig. 13.9 Dunlop cage deployed adjacent to the platform complex during the Seafish Mariculture project in 1998 during typical 1–2 m seas

to maintain the integrity of the cage. Damage would occur during a storm or heavy seas, repairs would be made quickly if time allowed between weather events, and then the next round of damage would occur. There were several thousand red drum stocked into the cage which grew well and the feed unit used on the project performed very well when the feed tube stayed attached as designed.

The project was ended abruptly and unexpectedly in 1999 when it was decided the cage needed to be moved as soon as possible to make room for pipeline construction in the area. Moving a large cage and moorings in the offshore GoM waters is a daunting task in perfect conditions and an impossible one in marginal or bad conditions. During this process the cage ended up entangled in the legs of a platform, the net was compromised, and for all practical purposes that was the end of the Seafish project. Several fish samples were taken along the way, but no significant amounts were ever brought to shore or harvested during the two year venture. A great deal was learned however in terms of what to expect and plan for during installation, feeding, and maintenance of large cage culture systems in the open GoM.

Though not directly utilizing a platform, there has also been one federally funded effort to conduct offshore aquaculture research in the GoM. This research took place from 2000–2003 and was initiated with the formation of the Offshore Aquaculture Consortium (OAC) which was a collaborative, Gulf-wide research and development program tasked with gathering primary scientific data regarding offshore aquaculture. The project site was in federal waters 40 km off the Mississippi coast at a depth of 26 m and within a few hundred meters of an active platform whose only involvement was for observation of the cage. The position of the OAC investigators was one of specifically not using a platform in an effort to have an autonomous cage system in the offshore Gulf waters. A commercially available Sea Station™ 600 m^3 system was installed with a single point mooring whose efficacy, ironically, was questioned at a workshop organized by the OAC in 2000. After being deployed for 50 days a component of the mooring failed and the cage was adrift for 40 days before being located and towed back to shore for repairs. The cage was subsequently redeployed with a three point mooring system and although fish were stocked into the system no significant amounts were harvested during course of the research. Funding was discontinued and unfortunately what began as an excellent opportunity for an offshore aquaculture demonstration project in the GoM ended abruptly in 2003. A detailed description of the entire OAC project can be found in the final report to NOAA (Bridger 2004).

13.4 The Future

Despite the challenging conditions, interest in offshore aquaculture production in the Gulf of Mexico still exists. From a technology standpoint, new and improved aquaculture systems are available that can survive and produce fish but the primary question is can this be done profitably offshore? Thus far, in the GoM the answer to that question has been no based on the experiences of the projects to date. A comprehensive economic feasibility study on using oil and gas structures in the GoM for mariculture concluded that at the present time it not likely to be a profitable venture (Kaiser et al. 2011a). Liability and decommissioning issues for the structure itself have long been identified as the major impediments to mariculture using platforms in the GoM and this situation remains true to the present (Dougall 1999; Kaiser et al. 2011a). The regulatory environment and permitting issues in offshore waters of the US have hindered development for two decades and investors have simply moved their offshore cage culture projects to other countries in many cases (Upton and Buck 2010). Internationally, there are only a couple of locations using dedicated platforms for mariculture production, one in the Mediterranean and the other in Japan. The platform in each case has multiple cages attached to it and acts as the operational center from which the growout systems are fed and maintained (Kaiser et al. 2011b). Considering the high energy environment, possibility for hurricanes, platform cost and liability issues, logistical challenges, and economic reality of offshore mariculture, it is not surprising there are no cage systems currently in the Gulf of Mexico.

That being said, it is the authors assertion that in the future a project with the right location, substantial capital investment, experienced personnel, and a good cage system will profitably grow fish in the Gulf of Mexico. The scenario will likely involve multiple submersible cages near a platform with a crane that houses a feeding unit capable of holding 200+ tons of feed which can be operated remotely if required. The structure may or may not be associated with an energy company and it may turn out that a platform put into place and designed specifically for a mariculture project, while certainly expensive, might be a better long-term option. The potential of refurbishing and reusing a decommissioned platform has also been suggested (Kaiser et al. 2011b) and may offer some advantages with regards to the liability issues that are associated with ownership.

An alternative to a platform proposed in the OAC final report is an aquaculture support vessel (ASV) which could be a large catamaran style vessel or more likely a lift boat type commonly used for nearshore maintenance on platforms (Bridger 2004). Several issues come to mind that make that option less attractive considering the high energy real world conditions in the GoM. Lift boats are very slow vessels (5–7 knots) that can only travel in decent seas—this complicates the logistics of anything in the 30+ km range. Because of depth requirements, these are the most likely areas for a cage project requiring tons of feed every day so faster crew boats would be required weekly to transfer the feed to a lift boat on a continual basis. In addition, once an operation is established with multiple cages and a substantial investment in fish stock, there can be no interruptions due to lift boat vessel maintenance, annual US Coast Guard inspections, and other mechanical issues. Because of this need for continual operation a second, backup ASV would be required for any large scale project that is conducted in GoM offshore waters. Assuming the cage site is in the preferred 30–50 m water depth, the cost of lift boats that can operate at these locations would be in the $5–20 + million dollars per boat range and would require the expense of two rotating teams of crew members as well. Lift boats cannot stay on site in all types of weather meaning that by pre-emptively heading in before severe conditions, not only are no personnel at the project site, but the feeders will not be getting filled on schedule, and fish will not be growing. Taken together, the cost of at least two ASV vessels, crews to man them, weekly supply boat runs, and the need for multiple feed buoys that must work flawlessly, the platform option starts to look better in comparison. Except for one hurricane evacuation during the Seafish project, the platform as a base of operations allowed personnel to remain on site continuously for two years regardless of the sea state and weather. This ability, combined with having a topside automated feed system instead of feed buoy(s) and virtually limitless feed storage capacity on multilevel decks begins to present a scenario where millions of kilograms of product could be cultured in the open ocean environment.

With regards to feeding, while a large buoy seems like an obvious alternative to using a platform there are several issues that warrant consideration for the GoM application of such a system. First, survivability of such a buoy is paramount since having several hundred thousand kilos of fish in culture is irrelevant if there is no way to reliably feed them. Designing a buoy that is able to maintain a specific position relative to the cages during normal choppy Gulf conditions, frequent 3–4 m seas, occasional 7+ m wave heights, and hurricanes is an engineering challenge at the very least. This technology is very expensive, but it has been demonstrated at an offshore site in New Hampshire (Fig. 13.10) and some of this research could be applied to future Gulf projects (Atlantic Marine Aquaculture Center 2007, http://ooa.unh.edu/). Feed barges up to 450 ton are used in protected waters (1–2 m) in Norway, Canada and Chile. Unfortunately, these pneumatic feeders would not survive in the GoM environment. Other possibilities for feeding a large scale farm include retrofitting a 40 m fishing vessel that can plug into a mooring and feed distribution system to each cage. If a severe storm is approaching, the vessel could detach and head back to port. Having a portable feeder would allow you to conduct maintenance, refueling, personnel exchange and fill the feed silos at a safe harbor instead of offshore. Offshore mariculture on a commercial scale involving millions of dollars of equipment and fish will likely need to be manned operations as well, a role that a platform and appropriate tender vessel could accomplish. Without thinking along this economy of scale involving systems that provide tens of thousands of cubic meters of water volume in which to grow marine fish offshore, the benefits of operating in the open GoM will not be realized.

Experiences gained after many years working on offshore aquaculture systems using platforms in the GoM can be distilled down into a partial list of some important points.

1. Eliminate modes of failure in all parts of the production system. Keep it strong and simple wherever possible as the offshore environment will reveal any component weaknesses, usually very quickly and often catastrophically.
2. Ocean conditions and weather determine everything offshore so plans must be made and adjusted accordingly. Nothing can be forced if conditions don’t allow it as the ocean will always win in that situation.

Fig. 13.10 Aquamana 20 ton feed buoy deployed at the University of New Hampshire Open Ocean Aquaculture site located 13 km offshore. The hydraulic feeder fed four submerged cages in sea conditions seas up to 10 m

3. Redundancy and backup systems where applicable, especially with regards to moorings, which are arguably the most critical components of the cage system.
4. Prepare as much equipment while the system is onshore as possible. It becomes exponentially more difficult to work on nets, stanchions, cage ties, shackles, and anchor lines the moment it enters the water.

The future of mariculture worldwide is a bright one. Demand for marine plants and animals is increasing and, while wild caught fisheries are essentially flat or in decline, the culture of these products is attempting to meet that demand with increased supply each year. Where the US fits into this future is unclear given our past record of low marine aquaculture production, onerous permitting requirements, and vague regulatory picture, especially in offshore waters. In the US, the Gulf of Mexico is an area that may play a role in domestic offshore mariculture production, should it ever develop on a commercial scale. This "audacious hope" for the GoM, as described in Sims (2015), will hopefully become a reality in the near future when the right concept is put into action with adequate investment. This will not happen, however, until the liability and regulatory issues in US federal waters and economic challenges of production are resolved in order make it a more attractive venture to investors.

References

Atlantic Marine Aquaculture Center. (2007). UNH Atlantic Marine Aquaculture Center. UNH, Durham, NH. Accessed January 12, 2016, at http://amac.unh.edu/

Bridger, C. J. (Ed.) (2004). *Efforts to develop a responsible offshore aquaculture industry in the Gulf of Mexico: A compendium of offshore aquaculture consortium research*. Ocean Springs, MS: Mississippi-Alabama Sea Grant Consortium. MASGP-04-029.

Chambers, M. D. (1998). Potential offshore cage culture utilizing oil and gas platforms in the Gulf of Mexico. In: C. E. Helsley (Ed.), *Proceedings of an International Conference on Open Ocean Aquaculture '97, Charting the Future of Ocean Farming* (pp. 77–87). April 23–25, 1997. Maui, HI: University of Hawaii Sea Grant College Program #CP-98-08.

Dougall, D. (1999). Platforms and fish pens-an operator's perspective. In R. R. Stickney (Ed.), *Proceedings of the Third International Conference on Open Ocean Aquaculture on Joining forces with industry* (pp. 39–43). May 10–15, 1998. Corpus Christi, Texas. TAMU-SG-99-103.

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change, 4,* 945–948.

FAO. (2009). *How to feed the world in 2050*. Rome, Italy, Food and Agriculture Organization of the United Nations. Accessed November 1, 2014, at http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

FAOFishStat. (2016). Retrieved August 1, 2016, from http://www.nmfs.noaa.gov/aquaculture/docs/aquaculture_docs/world_prod_consumtion_value_aq.pdf

Kaiser, J. B. (2003). Offshore aquaculture in Texas: Past, present, and future. In C. J. Bridger & B. A. Costa-Pierce (Eds.), *Open ocean aquaculture: From research to commercial reality* (pp. 269–272). Baton Rouge, LA: The World Aquaculture Society.

Kaiser, M. J., Snyder, B., & Pulsipher, A. G. (2011a). *Assessment of opportunities for alternative uses of hydrocarbon infrastructure in the Gulf of Mexico*. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study BOEMRE 2011-028.

Kaiser, M. J., Snyder, B., & Yu, Y. (2011b). A review of the feasibility, costs, and benefits of platform-based open ocean aquaculture in the Gulf of Mexico. *Ocean & Coastal Management*, *54*, 721–730.

NOAA FishWatch.gov. (2014) Accessed November 1, 2014, athttp://www.fishwatch.gov/farmed_seafood/in_the_us.htm

Oceanworld. (2014). Accessed November 1, 2014, at http://oceanworld.tamu.edu/students/fisheries/fisheries1.htm

Population Reference Bureau. (2003). Accessed November 1, 2014, at http://www.prb.org/Publications/Reports/2003/RippleEffectsPopulationandCoastalRegions.aspx

Price, C. S., & Morris, J. A., Jr. (2013). *Marine cage culture and the environment: Twenty-first century science informing a sustainable industry*. NOAA Technical Memorandum NOS NCCOS 164.

Sims, N. A. (2015). An audacious hope: To be able to grow fish in the Gulf of Mexico! *Aquaculture Magazine*. Retrieved January 23, 2015, from http://aquaculturemag.com/magazine/december-january-2014/2014/12/23/an-audacious-hope-to-be-able-to-grow-fish-in-the-gulf-of-mexico

UNEP. (2012). *United Nations Environmental Programme, Grid-Adrenal*. Accessed March 13, 2012, at http://www.grida.no/publications/rr/food-crisis/page/3562.aspx

Upton, H. F., & Buck, E. H. (2010). Congressional research service. *Open Ocean Aquaculture*. RL32694. Retrieved November 12, 2014, from http://www.respecttheocean.org/linked/congressional_doc.pdf

Part V
Conclusion and Outlook

Chapter 14
Epilogue—Pathways Towards Sustainable Ocean Food Production

Bela H. Buck and Richard Langan

Abstract While there is a great deal of global interest in the development of combined uses of open ocean installations, for commercial scale multi-use platforms for food and energy production and other potential applications, the transition from concept to reality has yet to come to fruition. While much is known about the economics, environmental, political and societal effects of individual production sectors, there are many unknowns and challenges with regard to economics, engineering, liability and social aspects of multi-use. Mutually agreed upon principles, such as those articulated in the Bremerhaven Declaration, and EU directives and grant funding opportunities to advance research and development indicate that progress, although measured, is being made. The development of true commercial-scale multi-use offshore platforms will require investment in demonstration projects and multi-national cooperation and collaboration across public and private sectors.

14.1 Introduction

In putting together this volume, we have attempted to capture the various aspects and complexities of implementing open ocean aquaculture as an additional use of offshore platforms. As we have stated in our introduction, we see great potential for

B.H. Buck (✉)
Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Marine Aquaculture, Maritime Technologies and ICZM, ZMFE Zentrum für Maritime Forschung und Entwicklung, Bussestrasse 27, 27570 Bremerhaven, Germany
e-mail: bela.h.buck@awi.de

B.H. Buck
Faculty of Applied Marine Biology, University of Applied Sciences Bremerhaven, An der Karlstadt 8, 27568 Bremerhaven, Germany

R. Langan
School of Marine Science and Ocean Engineering, University of New Hampshire, Judd Gregg Marine Research Complex, 29 Wentworth Road, Durham, NH 03854, USA

B.H. Buck and R. Langan (eds.), *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, DOI 10.1007/978-3-319-51159-7_14

maximizing the productivity of ocean installations for seafood, energy and scientific pursuits, and there has been a considerable amount of thinking and discussion that has taken place globally in recent years to realize this goal. We are deeply grateful for the contributions of the co-authors of this volume, as their expertise and experience represents the state of knowledge on the topic of aquaculture as a potential multi-use of ocean platforms.

We have covered technical, operational, biological, economic, social and political considerations, as well as case studies, where aquaculture was implemented at pilot scale on offshore oil rigs and wind turbine platforms.

One important area that was not covered in this book was environmental and ecological risks associated with aquaculture. While we acknowledge that environment issues are extremely important, we felt that they have been covered exhaustively over the past three decades and that further discussion would not have added new information for this volume. A recent review paper by the US Department of Commerce's National Oceanic and Atmospheric administration (Price and Morris 2013) does an excellent job of synthesizing thirty years of literature on all environmental aspects of marine fish cage culture, so we recommend that report to readers with interest of this topic. While most environmental impacts have been associated with marine finfish culture, there are some concerns with shellfish and macroalgae culture though to a much lesser extent. These issues are also covered extensively in the literature (Fabia et al. 2009; Hatcher et al. 1994; Langan 2007, 2012; Lloyd 2003; Paul 1999; Plew et al. 2005; Price et al. 2015)

14.2 What We Have Learned

While we have extensive knowledge of the technical, social, political, environmental and biological aspects of aquaculture and offshore energy as separate entities, we have less knowledge and experience with these activities taking place within the same ocean footprint. Though there are several projects in planning stages. Particularly in the EU, most of the projects to date have been small scale and have essentially been opportunistic retrofits on existing structures or hypothetical scenarios that have yet to be realized. We do know that there are complexities in site assessment and selection as well as permitting and licensing for aquaculture and energy installations as stand-alone activities, however, we do not know if the process would become even more complex if the two activities were proposed for the same project location, though we suspect they might.

We also know that there is potential for mutual benefits and cost savings for things like maintenance and operations, though the greatest advantage would be for aquaculture due to the robust structure provided by energy platforms to serve as attachment points for e.g. fish cages and bivalve and/or seaweed longlines and potential inclusion of feeders and possibly even hatcheries and nurseries mounted on the platforms. Additionally, any power requirements of the fish, shellfish and macroalgae farms could be provided by wind turbines.

14.3 What Still Needs to Be Learned

14.3.1 Technologies and O&M

The installation of aquaculture devices offshore, either in close proximity to or direct attachment to the offshore wind farm or oil rig, needs as a first step a full complement of oceanographic, environmental and site-specific data set as well as a full understanding of the water motions on the farm structure as well as its associated candidates. To avoid the major stress on the installation induced by storm conditions the aquaculture installations should be submergible. That means that a significant part of the entire culture unit is located beneath the surface and/or in direct contact to the multi-use platform, while the bulk of the structure's mass is mounted below the surface to allow buoyancy and stabilization. This mooring component should be below the zone of turbulence and wave action (Starchild 1980). None of these technologies and system designs are available on the market, nor are they currently in development.

Depending on the species and culture designs, more insight into the operation and maintenance including deployment and harvest by taking local site-specific criteria into account. As none of these multi-use devices currently exist or are only on pilot scale, O&M strategies cannot be developed except theoretically (see Chap. 4). To get more insight into this emerging issue, large-scale multi-use platforms have to be installed (see Sect. 14.5.1 below).

For some uses such as aquaculture, floating platforms already exist. However, for other uses such as wind farms and service platforms the floating design is in development. The combination of floating platforms in a multi-use concept is a new challenge and still in its initial stages (e.g. wind farm and desalination = Stefanakou et al. 2016; wind farms and aquaculture = TROPOS 2016; MERMAID 2016).

14.3.2 Environmental Impacts

As already mentioned above, volumes of information on risks from any type of aquaculture on the local ecosystem in the nearshore and offshore realm are available. However, potential risks originating from a combination of uses following the co-use concept is not known, especially when it comes to potential cumulative effects from wind energy turbines or oil rigs in association with aquaculture. The compilation of Beiersdorf and Wollny-Goerke (2014) provides information on ecological impacts resulting from offshore wind energy installations on the seabed and its associated organisms (Gutow et al. 2014). In addition, information on potential impacts on the pelagic habitat including invertebrates, ichthyofauna (Krägefsky 2014) and mammals (Dähne et al. 2014; Skov et al. 2014) as well as on avifauna and bat fauna (Damian and Merck 2014; Hill et al. 2014; Mendel et al.

2014) is available (Krause 2014; Kühn and Schneehorst 2014). A similar collection of information regarding the impact of oil rigs on the environment exists (e.g. Kingston 1992; Olsgard and Gray 1995) as well as from other offshore structures. However, when decommissioning these structures after their expected lifetime, the impact on the ecosystem can be quite diverse. That includes the fact that restoration of habitats may lead to a severe impact of organisms associated with the reef structure (Claisse et al. 2015; see also "Rigs-to-Reefs" program in Chap. 1 of this volume; Reggio 1987). Therefore, not only the impact of structures on marine habitats alone but also in combination depending on their respective use should be taken into account in future projects and/or commercial realisation.

14.3.3 Ownership and Insurance

As already addressed in Chaps. 10 and 13 ownership is an emerging issue currently not solved. Krause et al. (2011) indicated the importance of the social dimension of the different mariculture-wind farm integration processes and how this develops with regard to the various forms of ownership and management such a venture might take. The ownership versions discussed in Chap. 13, (1) sole owner, (2) negotiated contract, and (3) legislated contract, are only three possibilities among even more. Finally, for all current offshore users the political allocation of ocean space is licensed for specific purposes only not in combination with multi-users. In the future, there should be a new version of assignments of ocean space to avoid a complex mix of ownership, associated commons and private property.

The issue of having a shared insurance or every stakeholder its own insurance has not been addressed. This is even more complicated if the multi-use installation is owned or operated by one legal entity and a problem arises with one use having an effect on the other use (e.g. aquaculture installations will be dislodged during storm conditions and get entangled in the ships propeller of the wind farm maintenance vessel). There is an urgent need to come up with potential solutions.

14.4 Future Challenges and Opportunities

The combination of several activities (e.g. renewable energy, aquaculture, maritime transport, and related services) in the same marine space, including in multi-use platforms, it is quite possible that the costs of offshore operations and the demand on the space needed can be reduced. The research on multi-use platforms funded under the EU-Initiative FP7 call "The Oceans of Tomorrow" has already provided promising designs, technological solutions and models for combining activities in terms of economic potential and environmental impact. However, before reaching a demonstration pilot stage, further research is needed, which will be funded under the umbrella of two larger calls for proposals described below.

One barrier to multi-use the offshore realm is that different environmental, safety and regulatory regimes and practices apply to different sectors and to different national jurisdictions. Furthermore, there is a lack of common understanding of the nature of operations within different sectors and the feasibility of combining these in a way that provides mutual benefits. The first proposal call, "Multi-use of the oceans' marine space, offshore and near-shore: compatibility, regulations, environmental and legal issues" (BG-03-2016, 2 million Euros per proposal) was started in November 2016 (e.g. Project No. 17 "MUSES" in Chap. 13). The challenge is to identify the real and perceived barriers to integration. Therefore, there is a need for a clear overview of compatibility, regulatory, environmental, safety, societal and legal issues within the context of the maritime spatial planning directive and how they impact on the combining of different marine and maritime activities (EU 2016).

In the second proposal call, it is postulated that technological research and innovations are needed to reduce risks for operators and investors. Therefore, the call "Multi-use of the oceans marine space, offshore and near-shore: Enabling technologies" (BG-04-2017, 8 million Euros per proposal) was initiated in October 2016. The scope of the proposals should cover aspects with regard to combinations of innovative, cost-effective technologies and methods including automation and remote monitoring technologies, flexible structures and facilities in order to test concepts of multi-use platforms leading to pilot demonstration phases. Tests of the sustainable operability of co-located maritime activities around coastal or deep sea environments as well as health and safety issues associated with multi-use marine platforms should be addressed as well as environmental and economic viability and societal acceptance (EU 2016). However, as this call more or less covers a vast collection of emerging issues (offshore to nearshore, technology, economy, environmental issues, social issues, and many suggested multi-use combinations, etc.) we recommend to focus on the most promising multi-uses resulting from previous nation and international projects.

14.5 Recommendations to Accelerate Development in the Future

14.5.1 International Test Station

Scientists working in the field of offshore platforms, either for marine bio-resources or renewable energy and oil, agree that it is a very cost-intensive plan to install a larger aquaculture multi-use installation, which needs to be scaled up from scientific pilot scale to a size that simulates commercial production. It is therefore necessary to pool national and international expertise and resources to co-finance an offshore multi-use platform to allow the next step of research and development. This is even more important for other stakeholders interested in moving offshore, such as offshore (container) terminals for commercial shipping as well as offshore energy suppliers (used by energy consumers off the coast to avoid long sea passages to coastal harbours, such as fisheries, fish processing platforms, deep-sea mining, etc.), and other related services.

14.5.2 Bremerhaven Declaration

The initial concept for preparing the "Bremerhaven Declaration" was conceived at the "Marine Resources and Beyond Conference" conducted in 2011 and finalized in 2012 during the "International Workshop on Open Ocean Aquaculture", both held in Bremerhaven, Germany. Recognizing that the gap between demand and supply is increasing on a global scale, it is not surprising that the pressure to pursue offshore aquaculture development is growing. This is of prime importance in countries which are not able to install aquaculture operations nearshore. Some of these countries foster the concept of co-using offshore space. To better organize the wide range of scientific work in social, technological, economic and natural resources disciplines with focus on the co-use internationally, the Bremerhaven Declaration gathers issues on open ocean farming systems in co-management with the strong participation of other stakeholders interested in offshore natural resource uses, such as wind farms, oil rigs or other offshore installations. One major goal was to support inter- and transdisciplinary cooperation on local, national and international level and to avoid cost-intensive overlap of research. The participants believed that this would have the best output this agreement offers ample opportunities to bring aquaculture production to new levels.

A number of pertinent issues related to open ocean aquaculture and multi-use with other offshore installations was discussed, by

- **recognizing** that global food security, human health and overall human welfare are in serious jeopardy since the production of living marine resources for vital human foods cannot be sustained by natural fisheries production, even if these resources are properly managed at levels of optimum sustainable yields;
- **realizing** that the gap between seafood supply and demand is increasing at an alarming rate as these are nutrient-dense foods are considered extremely important for human health and well-being. On the other hand, the development of aquaculture has been remarkable and today provides more than half of all seafood destined for human consumption;
- **confirming** that conventional land-based and coastal aquaculture will continue to grow, thereby playing in the future a growing role in quality food supply. However, this much needed development will only delay the widening of the gap in seafood supply and new and modern technologies such as offshore farming systems are required to significantly assisting in closing this gap;

- **noting** that the world is too dependent, however, on aquaculture development and its exports, as aquaculture is threatened by coastal urbanization, industrialization, and water pollution. Weighing these trends we believe that it is urgent that the world develop offshore aquaculture, while complying with the FAO Code of Conduct for Responsible Fisheries and Aquaculture as well as with other environmental regulatory frameworks in support of sustainable aquaculture development;
- **finding** that Offshore aquaculture will require much higher inputs of capital but also needs a new level of cooperation from a wide range of social, technological, economic, and natural resource users;
- **discovering** that over the past decade major advances and new concepts have evolved, and several of them have been successfully tested at the pilot scale level, while others have failed.
- **learning** that these experiments and scale-up trials have led us to believe that offshore aquaculture does have substantial potential to bring global aquaculture production to new levels to meet future human needs;
- **believing** firmly that strategies need to be developed with strong participation of all affected stakeholders interested in the social-ecological design and engineering of innovative offshore aquaculture food systems;
- **recognizing** that the integration of offshore food and energy systems (e.g. aquaculture systems and windfarms; oil and gas) appear to be especially promising, but will require a high level of innovative technology, the use of marine spatial planning, and transparent, adaptive management for spatial efficiency and conflict resolution;
- **concluding** also that open ocean aquaculture if intelligently designed can be incorporate into overall cooperative fisheries restoration and management strategies.

The participants, which included a core group of the global expertise on the subject, formulated a series of specific recommendations and called upon national, international, intergovernmental agencies, as well as the industries, potential investors, scientists, regulators and NGOs of the respective countries to strongly support these recommendations with the aim to provide a healthy and environmentally sustainable bio-resource system that can substantially contribute to meet the future demands of our societies. All recommendations and justifications are summarised in Rosenthal et al. (2012a, b).

14.6 Conclusion

When we began this project several years ago, we were motivated by our firm conviction that a sustainable seafood supply for future generations is dependent on expansion of marine aquaculture and that open ocean environments are likely the best option for increasing production. We also recognized that maximizing the output of goods and services, in this case energy and food, from a human developed footprint of seafloor is key to wise ecological use of our oceans. While we concede that this is an enormous challenge that requires unprecedented commitment from a wide range of public and private sectors, we believe that the beneficial outcomes will far exceed the effort and investment. We applaud all efforts to move the multi-use concept forward and were pleased to see a recent article in an international aquaculture online publication encouraging its development (Holmyard 2016).

Our intent with producing this volume was to inform governments, research institutions and private industry about the potential for the multi-use concept, and to inspire these entities to continue the pursuit of transforming concept into reality. We hope that our efforts will contribute to the quest for creative solutions to food and energy production to the benefit of human health and well-being, and to ecologically sound and sustainable use of our oceans.

It is apparent that the orchestration of a multi-use concept, such as an integration of marine aquaculture with wind energy or oil production in the offshore realm, is still in its infancy. The major issue extracted from this volume clearly indicates that practical multifunctional use of offshore areas requires technical and economic feasibility as a basic prerequisite to assure that all operators will support a multi-use concept. Consequently, more information on the economic and technical viability of this joint venture is the key factor. If these issues will get more insight and result in best solutions, this will be a practical approach towards rationalizing marine stewardship in the offshore setting. The current initiatives on EU level are a perfect pre-condition to achieve this goal.

References

Beiersdorf, A., & Wollny-Goerke, K. (2014). *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives*. Wiesbaden: Springer.

Claisse, J. T., Pondella, D. J., Love, M., Zahn, L. A., Williams, C. M., & Bull, A. S. (2015). Impacts from partial removal of decommissioned oil and gas platforms on fish biomass and production on the remaining platform structure and surrounding shell mounds. *PLoS ONE*, *10*. doi:10.1371/journal.pone.0135812

Dähne, M., Peschko, V., Gilles, A., Lucke, K., Adler, S., Ronnenberg, K., et al. (2014). Marine mammals and windfarms: Effects of *alpha ventus* on harbour porpoises. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives*. Wiesbaden: Springer.

Damian, H. P., & Merck, T. (2014). Cumulative impacts of offshore windfarms. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives*. Wiesbaden: Springer.

EU (2016) Accessed October 20, 2016, at https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/calls/h2020-bg-2016-2017.html#c,topics=callIdentifier/t/H2020-BG-2016-2017/1/1/1/default-group&callStatus/t/Forthcoming/1/1/0/default-group&callStatus/t/Open/1/1/0/default-group&callStatus/t/Closed/1/1/0/default-group&+identifier/desc

Fabia, G., Manoukian, S., & Spagnoloa, A. (2009). Impact of an open-sea suspended mussel culture on macrobenthic community (Western Adriatic Sea). *Aquaculture, 289,* 54–63.

Gutow, L., Teschke, T., Schmidt, A., Dannheim, J., Krone, R., & Gusky, M. (2014). Rapid increase of benthic structural and functional diversity at the *alpha ventus* offshore test site. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives*. Wiesbaden: Springer.

Hatcher, A., Grant, J., & Schofield, B. (1994). Effects of suspended mussel culture (*Mytilus spp.*) on sedimentation, benthic respiration and sediment nutrient dynamics in a coastal bay. *Marine Ecology Progress Series, 115,* 219–235.

Hill, R., Hill, K., Aumüller, R., Schulz, A., Dittmann, T., Kulemeyer, C., et al. (2014). Of birds, blades and barriers: Detecting and analysing mass migration events at *alpha ventus*. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives*. Wiesbaden: Springer.

Holmyard, N. (2016). Can aquaculture flourish in a more symbiotic sea? Accessed October 19, 2016, at http://advocate.gaalliance.org/can-aquaculture-flourish-in-a-more-symbiotic-sea/ October 19, 2016.

Kingston, P. F. (1992). Impact of offshore oil production installations on the benthos of the North Sea. *ICES Journal of Marine Science, 49,* 45–53.

Krägefsky, S. (2014). Effects of the *alpha ventus* offshore test site on pelagic fish. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives* (pp. 83–94). Wiesbaden: Springer.

Krause, G., Griffin, R. M., & Buck, B. H. (2011). Perceived concerns and advocated organisational structures of ownership supporting "offshore wind farm–mariculture integration". In G. Krause (Ed.), *From turbine to wind farms–technical requirements and spin-off products*. Rijeka, Croatia: InTech, Open Access Publisher.

Krause, J. (2014). Conservation features: Sensitive species and habitats in the German exclusive economic zone. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives* (pp. 39–44). Wiesbaden: Springer.

Kühn, B., & Schneehorst, A. (2014). Oceanographic and geological research at *alpha ventus*: Instruments for predicting environmental conditions and interactions. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives* (pp. 53–65). Wiesbaden: Springer.

Langan, R. (2007). Results of environmental monitoring at an experimental offshore farm in the Gulf of Maine: Environmental conditions after seven years of multi-species farming. In C. S. Lee & P. J. O'Bryen (Eds.), *Open ocean aquaculture—Moving forward* (pp. 57–60). Waimanalo, Hawaii: Oceanic Institute.

Langan, R. (2012). Mussel culture: Innovations in deep water. In: B. A. Costa-Pierce & G. G. Page (Eds.), *Sustainability science in aquaculture*. *Encyclopedia of sustainability science and technology*. doi10.1007/978-1-4419-0851-3

Lloyd, B. D. (2003). *Potential effects of mussel farming on New Zealand's marine mammals and seabirds: A discussion paper*. Wellington, NZ: Department of Conservation.

Mendel, B., Kotzerka, J., Sommerfeld, J., Schwemmer, H., Sonntag, N., & Garthe, S. (2014). Effects of the *alpha ventus* offshore test site on distribution patterns, behaviour and flight heights of seabirds. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives* (pp. 95–110). Wiesbaden: Springer.

MERMAID (2016) Accessed October 27, 2016, at http://www.vliz.be/projects/mermaidproject/

Olsgard, F., & Gray, J. S. (1995). A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. *Marine Ecology Progress Series, 122,* 277–306.

Paul, W. (1999). Reducing the risk of open ocean aquaculture facilities to protected species. In NOAA (Ed.), *National strategic initiative project, summaries 1999* (pp. 1–11). Aquaculture Information Center: DOC/NOAA.

Plew, D. R., Stevens, C. L., Spigel, R. H., & Hartstein, N. D. (2005). Hydrodynamic implications of large offshore mussel farms. *IEEE Journal of Oceanic Engineering, 30,* 95–108.

Price, C. S., & Morris, J. A., Jr. (2013). *Marine cage culture and the environment: Twenty-first century science informing a sustainable industry* (Vol. 164). NOAA Technical Memorandum NOS NCCOS.

Price, C. S., Morris, J. A., Keane, E., Morin, D., Vaccaro, C. & Bean, D. (2015). *Protected Species and Mussel Longline Interactions*. NOAA Technical Memorandum NOS/NCCO.

Reggio, V. C. (1987). *Rigs-to-Reefs: The use of obsolete petroleum structures as artificial reefs*. New Orleans: U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, (OCS Report MMS 87-0015).

Rosenthal, H., Costa-Pierce, B. A., Krause, G., & Buck, B. H. (2012a). Bremerhaven declaration on the future of global open ocean aquaculture, part I: Preamble and recommendations. Aquaculture forum on open ocean aquaculture development—From visions to reality: The future of offshore farming. Funded by: Investment in sustainable fisheries co-financed by the European Union (European Fisheries Fund—EFF), Ministry of Economics, Labour and Ports (Free Hanseatic City of Bremen), The Bremerhaven Economic Development Company Ltd.

Rosenthal, H., Costa-Pierce, B. A., Krause, G., & Buck, B.H. (2012b). Bremerhaven declaration on the future of global open ocean aquaculture—Part II: Recommendations on subject areas and justifications. Aquaculture forum on open ocean aquaculture development—From visions to reality: the future of offshore farming. Funded by: Investment in sustainable fisheries co-financed by the European Union (European Fisheries Fund—EFF), Ministry of Economics, Labour and Ports (Free Hanseatic City of Bremen), The Bremerhaven Economic Development Company Ltd.

Skov, H., Heinänen, S., Arreborg-Hansen, D., Ladage, F., Schlenz, B., Zydelis, R., et al. (2014). Marine habitat modelling for harbour porpoises in the German Bight. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological research at the offshore windfarm alpha ventus: Challenges, results and perspectives* (pp. 151–169). Wiesbaden: Springer.

Starchild, A. (1980). Seaward Ho!—The ocean frontier. In Office of Technology Assessment (Ed.), *Energy from open ocean kelp farms* (pp. 83–98). University Press of the Pacific.

Stefanakou, A., Dagkinis, I., Lilas, T., Maglara A., & Vatistas, A. (2016). Development of a floating wind-desalination multi-use platform (MUP) in the context of optimal use of maritime space. In *Offshore energy and storage symposium (OSES) and industry connector event*. University of Malta, Valletta, Malta 13–15 July 2016.

TROPOS (2016) Accessed October 27, 2016, at http://www.tropos platform.eu/