Appraisal of the opportunity for offshore aquaculture in UK waters

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EXECUTIVE SUMMARY

This report provides an assessment of the potential for open ocean, offshore finfish aquaculture in UK waters using candidate species which would have similar growth and performance characteristics to Atlantic salmon (*Salmo salar*) and Atlantic cod (*Gadus morhua*) and with due reference to other potential species candidates.

The appraisal addresses economic, financial and marketing issues, with specific reference to scenarios generated with respect to a conceptual large-scale open ocean mariculture system. The environmental, legal and technical implications for offshore aquaculture development are examined in a general context.

This desk-based appraisal draws principally on published information, together with data derived from appropriate sources with acknowledged expertise.

A projected financial analysis is provided of production taking into account routine market price fluctuations and potential impacts of such a system's production on the marketing of existing farmed and/or wild caught production.

The potential market and impact of fish produced within offshore systems is assessed, taking into account quality assurance and consumer/retail acceptance of products grown in aquaculture systems offshore.

The ecological considerations of offshore cultivation are overviewed, taking into account potential environmental impacts of such an operation.

A general consideration of the legal aspects which may be associated with establishing offshore aquaculture systems is provided, taking into account the possible impact of current and proposed legislation.

Examples of available and planned production systems which may be suitable for use in exposed and potentially, offshore UK waters are reviewed. Critical biological and technical aspects of offshore finfish cultivation are examined. The potential use or reuse of existing and planned offshore installations is discussed.

The report highlights some deficiencies in technical capacity, biological understanding and legal impediments that may stifle attempts to conduct aquaculture offshore. However, the report provides some strategic conclusions with respect to the potential future development of aquaculture in more exposed and potentially offshore locations.

If pilot scale projects are to be taken forward these should, in the first instance, be conducted within the 3nm limit. Furthermore, many of the biological and technical precursors which would be required to underpin the viability of offshore aquaculture could potentially be tested with existing cage systems in appropriate exposed sites.

Offshore aquaculture is fundamentally appealing and could be strategically important to the UK in the future. The evidence provided suggests that careful consideration of properly justified calls for R&D is merited in support of aquaculture development in more exposed locations with a view to better defining the prospects for full offshore operations in the future.

For those with limited time, the authors recommend reading the INTRODUCTION (Sections 1 – 1.1.2) and the CONCLUSIONS (Sections 7 – 7.5).

CONTENTS

1. INTRODUCTION

The aim of this appraisal is to provide a critical assessment of the potential for open ocean offshore aquaculture in UK waters using candidate species which would have similar growth and performance characteristics to Atlantic salmon (*Salmo salar*) and Atlantic cod (*Gadus morhua*) and with due reference to other potential species candidates.

The appraisal addresses economic, financial and marketing issues, with specific reference to scenarios generated with respect to a conceptual large-scale open ocean mariculture system. The environmental, legal and technical implications for offshore aquaculture development are examined in a general context.

This desk-based appraisal draws principally on published information, together with data derived from appropriate sources with acknowledged expertise.

This report addresses five principal objectives:

Objective 1: A projected financial analysis of production (including operational costs, feed cost and supply, stock health costs, and juvenile cost and supply), taking into account routine market price fluctuations and potential impacts of such a system's production on the marketing of existing farmed and/or wild caught production.

Objective 2: Assess the potential market and impact of fish produced within offshore systems, taking into account quality assurance and consumer/retail acceptance of products grown in aquaculture systems offshore and especially those sited in the vicinity of existing offshore oil and gas production platforms.

Objective 3: Provide an overview of ecological considerations, taking into account potential environmental impacts of such an operation, including reference to escaped stock.

Objective 4: Provide an overview of the legal aspects associated with offshore aquaculture systems, taking into account the possible impact of current and proposed legislation.

Objective 5: Provide an overview of currently available and planned offshore production systems which may be suitable for use in UK waters, taking into account design, operational logistics and management.

1.1.1 Defining Offshore Aquaculture

Various definitions of "offshore aquaculture" have been proposed with a view to providing a framework within which the technology, principally cage design, can be developed. The Norwegian Government classifies sites based on significant wave height (Hs)[1].

Table 1. Norwegian aquaculture site classification scheme (after Ryan, 2004).

Site Class	**Significant Wave Height (Hs)(Meters)**	**Degree of Exposure**
1	<0.5	Small
2	0.5-1.0	Moderate
3	1.0-2.0	Medium
4	2.0-3.0	High
5	>3.0	Extreme

[1] The average height of the highest one third of waves recorded in a given monitoring period. Also referred to as H⅓ or Hs.

Muir (2000) argues for a much broader, systems approach to defining offshore conditions and the suite of variables that should be considered in developing offshore aquaculture. In order to define basic criteria and thus clarify what is required for offshore aquaculture, Table 2 summarises some of the key distinctions between more common coastal (inshore) and offshore production (Muir, 1998; see also Willinsky and Huguenin, 1996).

Table 2. Key distinctions of offshore aquaculture (Muir, 1998).

Characteristics	**Coastal (inshore)**	**Offshore aquaculture**
Location/hydrography	05-3 km, 10-50 m depth; within sight, usually at least semi-sheltered	2+ km (>1nm), generally within continental shelf zones, possibly open-ocean
Environment	Hs <=3-4 m, usually <=1 m; short period winds, localized coastal currents, possibly strong tidal streams	Hs 5 m or more, regularly 2-3 m, oceanic swells, variable wind periods, possibly less localized current effect
Access	>=95% accessible on at least once daily basis, landing usually possible	Usually >80% accessible, landing may be possible, periodic, e.g., every 3-10 days
Operation	Regular, manual involvement, feeding, monitoring, etc.	Remote operations, automated feeding, distance monitoring, system function

In the US, offshore aquaculture, also referred to as open ocean aquaculture, has been defined as "the rearing of marine organisms under controlled conditions in the exclusive economic zone (EEZ) – from the three mile territorial limit of the coast to 200 miles[2] offshore." Facilities may be floating, submerged or attached to fixed structures.

In addition to the above, other factors also need to be taken into account with respect to site selection for a range of technical, biological, economic, environmental and legislative criteria. Whilst there are some isolated examples of what could be described as offshore production, progress in this field has been uncertain and relatively slow (see Muir, 2000). For the purposes of this study, we are adopting the definition of "offshore" proposed in Table. 1 (equivalent of Class 4 and above sites) and Table 2, with the focus being principally but not exclusively, on sites beyond the 12nm limit (UK Territorial waters). The reason for this prescription is that whilst offshore conditions as defined above occur within this limit, the legislative regime to govern fish farming activities within it is, to a large extent, already defined. However, regulation between the 12nm limit out to the UK 200nm EEZ has not been developed with a view to accommodating offshore fish farming and the logistics of operating at distances which precludes the use of shore bases has not been examined in any detail.

The term "mariculture" has also been used in various ways in the literature to identify extensive or non-intensive marine aquaculture and to describe cultivation for the purposes of marine finfish restocking. In the context of this report these terms are interchangeable and simply refer to the cultivation of marine animals and plants in the sea. Similarly, the terms "cages", "net pens" and "enclosures" are not used in a pejorative sense, are also interchangeable, and refer to the means used to confine the fish.

[2] Miles refers to nautical miles

1.1.2 Background

Many of the arguments surrounding the potential and need for the development offshore aquaculture are well rehearsed (e.g. Benetti, et al., 2006; Ryan, 2004; Muir and Basurco, 2000; Helsley, 1998; Polk, 1996). A significant driver for moving coastal cage farming to more exposed or even offshore sites are real or perceived constraints on carrying capacity and increasing pressures on coastal habitats from many resource users, making site acquisition for mariculture development increasingly difficult. Moving offshore could potentially reduce environmental impacts, reduce disease and improve fish performance but, as yet, there is little scientific evidence to support these claims. In addition, it is possible that offshore production will require that fish are put to sea at larger size (increasing juvenile costs), much more sophisticated technology will be required for remote fish husbandry, cage construction materials and operational procedures may have to take into account species-specific requirements, adding to operational costs.

There is a clear trend towards larger production unit sizes (FRS, 2005) and in some areas sites being operated at an increasing distance from the shore. The main reasons for such gradual exploration of more exposed waters rather than open-ocean waters are that operating and infrastructure costs as well as the infrastructure support systems are similar to existing inshore farming systems. Pilot-scale experiments and commercial operation for more exposed cage systems developed out of conventional cages through step-by-step enlargement and structural improvements have been reported from Ireland, Norway, Italy and Spain (ICES WGEIM, 2005).

Very few commercial-scale offshore developments have occurred so far. High cost of both the system purchase and its operation are critical factors, hence there is relatively little practical experience of offshore fish farming available. Muir (2000) estimated that at that time, the total offshore production worldwide was of the order of only 5,000 tonnes – in 2006, the total is still probably less than 10,000 tonnes. However, there is a growing body of research in this area and a general view amongst some commentators that we should adopt a strategic vision of aquaculture which includes offshore development (e.g. Turner, 2000; Bridger and Costa-Pearce, 2001; Pérez *et al.*, 2003; Ágústsson, 2004; Buck, 2004; Ryan, 2004).

The theoretical potential for taking cage aquaculture offshore has been recognised for many years, but the risks and cost of entry into the offshore environment have limited commercial interest. In addition, fears that the industry would be excluded from inshore areas on the grounds of environmental impact have not been realised and there are indications that a more sustainable balance of production against environmental carrying capacity is being struck (see for example – Strategic Framework for Scottish Aquaculture - www.scotland.gov.uk/library5/environment/sfsa-00.asp March 2006).

With respect to the UK, marine cage aquaculture almost exclusively takes place in Scottish coastal waters. Whilst the number of production sites in Scotland is now clearly limited, some evidence suggests that the capacity at many sites is perhaps underutilised. Recent production figures have shown, for the first time since records began, a reduction in production of approximately 6.9% from 169,736 tonnes in 2003 to 158,099 tonnes in 2004 (FRS, 2005).

Marginal levels of profitability in the salmon production sector in recent years, coupled with relatively low whitefish prices for species such as cod from wild fisheries have further stifled interest in the development of finfish aquaculture in northern European waters generally. The price of whitefish may be an anomaly caused by the capacity of the UK to continue to import fish from what may be less regulated or more abundant stocks elsewhere. The only realistic prospect for volume whitefish aquaculture at this time is cod, but the costs of producing this species through aquaculture still renders it economically marginal, except for the luxury market (see page 35). Salmon prices have been notoriously volatile and profitability has been marginal in recent years. Whilst the market for this species can be shown to be expanding generally, there still appears to be excess production capacity in some areas.

In the longer term, if landings of fish decline globally and the demand for fish such as cod and salmon expands, there will be pressure to increase inshore capacity. For the UK and Scotland in particular, whether or not this translates into the development of offshore production will be very much dependant on whether the costs of increasing capacity in the offshore environment are sustainable against production from Norway, Chile and elsewhere.

In examining the offshore aquaculture proposition, it is important to identify what form such development might take. Using the criteria of Muir (1998) (see Table 2) it is clear that farms could be established in offshore conditions, sufficiently close to shore to allow remote access with reasonable frequency. With increasing distance offshore infrastructure capable of housing personnel and other farm support services would be required. These facilities could be provided by platforms or through dedicated support vessels. In principle, existing and planned offshore structures such as oil and gas production platforms could be utilised, together with modified fishing vessels for example (decommissioning rules would not preclude the reuse of fishing vessels).

The US Government has recently relaxed its position on offshore aquaculture and the US National Offshore Aquaculture Act of 2005 will allow commercial offshore fish farming. The legislation was developed by the National Oceanic and Atmospheric Administration (NOAA) to provide a regulatory framework for the development of offshore aquaculture beyond the 5.5km (~3nm) State boundaries out to the EEZ. This action will further stimulate interest in offshore aquaculture. To date, a few pilot systems have been tested, but none operate on a consistent commercial scale. Buck (2004), summarises these developments (e.g. Loverich 1997, Loverich & Gace 1997, Braginton-Smith & Messier 1998, Loverich 1998, Loverich & Forster 2000). These efforts led to the idea to include various disused oil platforms in the Gulf of Mexico (GOM) in a multi-use concept (Miget 1994, Wilson & Stanley 1998). In addition, the National Sea Grant College Program funded the Open Ocean Aquaculture Program at the University of New Hampshire (Ward *et al*., 2001) and the Hawaiian Offshore Aquaculture Research Project (HOARP) (Ostrowski & Helsley 2003).

The Louisiana Oil Platforms for Mariculture Task Force, in its recommendations to the Louisiana Legislature and Governor (Anon, 2005), propose that "Federal legislation and policy initiatives for the Gulf Of Mexico (GOM)) Exclusive Economic Zone (EEZ) mariculture activities should be aggressively monitored to assess implications on the development of a mariculture industry in Louisiana". Given that the GOM has the world's largest concentration of offshore oil rigs (~4,000 see http://www.lsu.edu/sglegal/pdfs/Platforms_Mari.pdf) – many of which are due for costly decommissioning, coupled with the pressure for Federal investment in the Louissiana coastal area in the wake of hurricane Katrina in 2005, it would seem likely that attempts to use existing offshore structures will increase. However, attempts to develop aquaculture in association with production platforms in the GOM have so far failed and issues of liability with respect to the ultimate decommissioning of these structures will need to be addressed before any form of commercial scale aquaculture is considered. Without some form of dispensation or financial support, it would seem unlikely that aquaculture operations would generate revenues which would accommodate the considerable costs associated with decommissioning existing structures.

A consortium led by the Hubbs–SeaWorld Research Institute of San Diego, hopes to anchor two square kilometres of nets on a former Chevron oil-drilling platform, about 20km off the coast, and fill the nets with tuna and other deep-water fish. The project would begin as a research facility, examining the capability of offshore farms and their environmental impact. The non-profit institute plans to extend operations to a commercial venture, using millions of dollars from fish sales to support the facility and its research. According to some reports, Chevron is funding the institute's start-up costs and offering $10 million to run the operation for three years. The oil company hopes to avoid the substantial expense of removing the oil platform completely. However, this project was to start in 2004 and there is no current information on the status of this venture on either the

Institutes website or the dedicated project website (http://www.gracemaricultureproject.org – March 2006).

As oil and gas supplies decline in the UK, many offshore oil and gas installations are scheduled to be decommissioned. The decommissioning process may involve removal of contaminated drill cuttings form the seabed, but for most installations the main requirement is for the structure above the seabed to be removed with only the concrete moorings and well caps remaining (http://www.ukooa.co.uk/issues/decommissioning/options.htm - March 2006; http://www.og.dti.gov.uk/upstream/decommissioning/index.htm - March 2006). The cost of decommissioning is significant and whilst the UK Government is liable for a significant proportion of this cost, one would anticipate that offshore operators would be interested in prolonging the active life of such facilities to further spread their liabilities and costs. Increasing oil and gas prices together with new technology have encouraged operators to extend the life of many platforms (often well beyond their original design specification). It has been suggested that operational platforms and platforms due to be decommissioned could be utilised for the development of offshore aquaculture. No formal assessment of this proposition appears to have been conducted in UK waters.

Cursory analysis would suggest that the liability of decommissioning would not be mitigated to any great extent by utilising these facilities for aquaculture. In comparison to oil and gas, aquaculture is not particularly profitable and would be unlikely to generate sufficient revenues to cover the cost of decommissioning or the more immediate costs of maintaining structures which have, in many respects, reached the end of their operational and design life. Combining offshore aquaculture development with existing production facilities is perhaps an option worthy of investigation, if the major expenses related to the maintenance of the structure were largely met by the operator; the rig itself serving as a basic service facility for personnel, feed storage and logistics etc., for an offshore farm. However, aquaculture activities would undoubtedly be a minor part of the revenue stream generated by such an operation and, given the potential for conflicts of operational interest, co-production (at least in the vicinity of the platform) may not be of interest to an offshore oil and gas operator.

The growth of the offshore renewables sector in UK waters will be significant over the next twenty to thirty years (http://www.bwea.com – March 2006). Developments of this kind may be capable of accommodating aquaculture production, particularly if production systems which fit with these developments evolve in parallel. There are several reasons why aquaculture operations might be interested in farming within the confines of a designated offshore renewables site:

1. As for associations with other established offshore operations there might be economies achieved by co-use of logistics and facilities.
2. Conflicts with others users of the marine environment may be reduced – if for the purposes of navigation or fishing etc., they are, by default, excluded from such areas.
3. Some offshore structures may afford aquaculture operations physical protection from excessive wind and wave action.
4. Direct access to electrical power could reduce operating costs and open up opportunities for increased photoperiod production together with increased levels of automation and remote operation.

Quite understandably, some wind farm operators are cautious about encouraging any activity which could potentially interfere with or damage the operation or infrastructure of the wind farm. Fishing activities such as trawling and dredging may, for example, not be permitted within some the wind farm arrays (see for example; http://www.londonarray.com/faq/offshore-faq - March 2006). It seems possible that some forms of static gear deployment could be accommodated, if deployed in ways which do not affect the passage of vessels involved in the operation of the wind farm or impact on sub-sea infrastructure.

With respect to aquaculture, if the conditions are suitable, it is possible that some forms of production could be undertaken. Buck (2004) has conducted some preliminary trials with laminaria and mussel production in offshore conditions. Indications are that some form of long-line mussel culture would be worthy of a pilot scale trial in the UK. The number of proposed sites which would be suitable for finfish production is likely to be somewhat more limited by a combination of wave climate (see below), depth and more complex operational requirements. In line with the preference of wind farm operators to maintain open navigable channels within the farm site, all cage structures and ancillary equipment would need to be submersible. Single point mooring cage designs may not be appropriate if the foot print of their travel impinges upon the desired area of exclusion around turbine pylons or proximity to cables and other sub-sea infrastructure. Multipoint moorings may afford more positional stability and less risk in the event of mooring failure, but there would be a greater chance of interference with sub-sea infrastructures. Given the need for stock husbandry in fish farming activities, coupled with higher capital investment, it is possible that there would be greater chance of conflict of interest between the wind farm operator and the fish farmer.

Of greater interest, theoretically at least, is the potential to combine aquaculture and finfish culture in particular, with offshore wave power development. Some of the surface and near surface wave power generation devices, clearly have the potential to act as baffles; reducing wave energy and creating wave climates in their wake which might be favourable to some forms of cage culture. Whilst similar caveats may apply with respect to the operation of fish farms in close proximity to the wave power generator as for wind farm sites, the prospects for a more equitable association seems possible.

These scenarios are, however, highly speculative and a more detailed assessment is required, which would bring together renewables operators with those commercially engaged in aquaculture. Only by so doing, will practical understanding emerge and pragmatic and realistic solutions evolve. It is for aquaculture to prove that it can be conducted successfully alongside offshore renewables and to do so will demand the development of trust. The latter will only be achieved if rational, well planned and expertly conducted pilot scale developments are established. Ill-conceived and naive attempts to develop aquaculture in collaboration with this emerging industry are likely to undermine confidence and significantly hinder progress. However, on the basis of this report, it would seem reasonable to attempt to formalise links between the offshore energy production sector and aquaculture interests with a view to developing a more informed approach, which might stimulate interest and reveal opportunities for collaboration.

2. PROJECTED FINANCIAL ANALYSIS OF PRODUCTION

2.1 ECONOMIC MODELLING

2.1.1 Basics of Aquaculture Economics

Fish farming is a business, fundamentally similar to all other businesses in the developed world. It starts with a market proposition that supposes consumers want to buy the farmed fish at a sensible price (and with all the caveats of quality, reliability of supply, value for money, food safety, convenience, health benefits, etc). It continues with the elaboration of a production technology that:

- produces the fish at a cost which is sufficiently below the price consumers are prepared to pay for the product, such that;
- a good profit is made, including covering all financial costs of debt capital, and;
- providing sufficient dividend potential that investors achieve a 'rate of return' on their investment which covers their perception of the risk of the investment when it was first made, perhaps as one of several alternative investments they could have made.

The latter point becomes somewhat more complex in a start-up situation such as farming in a new place with new technology, when one considers that there are two fundamental ways of achieving a return on an investment: over the long term, as dividends; or over a shorter term by way of selling a business which has been grown. Of course the first option – long term profitability – is the fundamental key to business success. However, it is not necessarily the main attraction to all investors when considering a new business start-up.

The first point above (a system and process with a satisfactory cost-of-production) encompasses all the difficult and detailed pieces of modelling which have to be undertaken. These require some basic understanding of biological processes, so that estimates of production timescales and direct costs can be made. Engineering systems and other aspects of technology also have to be clearly understood, so that fixed asset investment costs and some key operating costs can be accurately forecast.

Even the basic premise of 'producing a fish which the consumer wants' has to be explored in more detail. Does the consumer want the skin, bones and viscera as well as the flesh? If the flesh is the important thing, do all fish species produce the same amount of 'yield' for a similar amount of input to producing the whole animal?

A good aquaculture financial model takes all the above factors into account, and is as much a biological and technical model as it is an economic one. However, no matter how interesting, varied or novel the technical and biological features might be, the model must always end up with a simple financial premise – or question: does this business make enough money to attract an investment from a source which has no interest other than making a good rate of return?

Aquaculture is now a relatively mature industry, and would-be-investors have a lot of history upon which to draw. Some of it was not very positive, particularly in the early years: ill-conceived projects promulgated by enthusiastic biologists or inventors of pieces of 'kit' which they wanted to sell. The industry is well beyond that phase now, and any new aquaculture plan has to be detailed, meticulous, based upon hard demonstrable fact – and profitable.

The various modelling iterations undertaken in this study will hopefully address all the issues raised above. They will utilise the best information which is available, and where it is not they will use the most experienced assumptions that can be made.

2.1.2 Sources of Information on Aquaculture Economics

There is a relative scarcity of good public-domain information about aquaculture economics. Several publications give some indication of basic annual production figures, and this study will draw on some of the most recent of these (Posadas *et al.,* 2001; Slaski, 2001; Slaski, 2002; Slaski, 2003; Ryan, 2004; KPMG, 2005). They do not necessarily give a clear picture of the full investment consideration for aquaculture projects. This scarcity is not surprising, since such in-depth analysis is usually commissioned under strict terms of commercial confidentiality.

However, for the current study a detailed modelling tool has been developed. Inputs (factual or best-guess assumptions) are derived from public domain sources, and thus the model outputs are capable of public domain dissemination. These outputs will be in a more 'investor-focused' format than is commonly seen, and should therefore be of enhanced benefit to those interested in the concept of offshore aquaculture.

2.1.3 Offshore Aquaculture Studies

2.1.3.1 Ryan (2004)

An important source of background information for some of the assumptions used in this study is Ryan (2004). The paper contains a useful, comprehensive and recent review of the various 'offshore aquaculture' projects which have been or are under trial in different parts of the world. It also clearly identifies the need for such technology to be developed, if the so-called 'FAO Gap'[3] is to be filled in the coming decades.

Ryan presents a number of considerations or observations which must be taken into account when considering an offshore aquaculture installation:

- There is a broad assumption that submerged pen technology will probably be required for Class 4 (fully oceanic) locations. Although an intermittently submersible (in the event of bad weather) technology might be applicable.
- There is some doubt about whether Atlantic salmon are physiologically suited to submerged conditions, having a need to ingest surface air from time to time as part of their swim bladder buoyancy control mechanism. Although some system designers have incorporated 'domes' of trapped air within fully submerged structures, which would, in theory, deal with this problem.
- The issue of low fillet yield for certain target aquaculture species is discussed, and acknowledged to represent a challenge to the economics of such a venture.
- The poor history of the projects centred on the Gulf of Mexico oil platforms is discussed.
- The paper acknowledges that absolutely certain technical solutions to key operating challenges have not yet been achieved. These include: grading within the farm; net cleaning; harvesting manageable quantities from large enclosures; constant access for predictable feeding, health and welfare care, and harvesting.

Ryan presents a hypothetical model for a concept 10,000 tonne per annum (tpa) production unit, based upon anchor tension cages located in a Class 3 site, i.e. a site which is not fully open ocean, but which benefits from some degree of shelter from wave and current action.

Theoretical financial models for the operation of such a site, based upon the cultivation of Atlantic salmon are provided. The initial 'core model' suggests that at a production scale of 10,000 tpa, a margin of some EU 422 per tonne might be achieved. The assumed sales price for salmon is EU 2,970 per tonne (whole fish equivalent, delivered), which is not an unreasonable estimate of the averaged sale price for salmon in the EU over the years 2001 to 2004 inclusive.

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[3] FAO – Fisheries and Agriculture Organisation

However, the author does not project this model further into some basic investment-decision indicators which would be needed before such a project was considered. For example:

- A ten year discounted cash flow analysis of Ryan's core model might deliver an internal rate of return (IRR) of 12%, which might be considered low by many analysts, particularly bearing in mind the risk of the project, and the requirement to make an initial funding decision of at least EU 48 million before first sales income starts to appear.

- If the project required (for example) a 50% debt capital financing structure (again over a 10 year term, and based on 6% interest), then debt repayments would wipe out almost all positive cash flow on an annual basis.

On the basis of these indicators, the Ryan's 'core model' might be of limited appeal to commercial investors.

Ryan does present various modified scenarios based upon additional efficiency assumptions, and these do suggest a more attractive prospect for investors. These sorts of efficiencies are probably required anyway by the existing industry as a whole, and therefore to identify and strive towards them seems entirely appropriate.

Ryan concludes that further development of offshore aquaculture technology requires a holistic and multi-partner approach, including both the public and private sectors, and probably based on international collaboration.

2.1.3.2 Maris Fish Ranches Ltd

This study has had access to commercial-in-confidence material from a UK company that is promoting offshore aquaculture technology. The material has been derived from a number of sources, which include well-respected engineering and marine sciences bodies.

Whilst respecting the commercial-in-confidence, this study draws upon some of the information provided by Maris in a non-attributable fashion, merging it with information drawn from other sources.

2.1.3.3 Posadas et al. 2001

Posadas *et al.* (2001) modelling the farming of several different species of warm water fish in the Gulf of Mexico, and largely conclude that only one species, Cobia, might provide a sufficient return on investment. Interestingly the authors conclude that an Internal Rate of Return (see page 26) of just over 14% might make such a venture 'feasible'.

The study also presents some indicative fixed asset costs. For example, they propose that the total cost (including shore installations) for a farm of 36,000m^3 would be 4.35 million USD. This is significantly higher, per unit volume, than the assumptions made by Ryan and others, and used as the basis of modelling in this study.

2.2 BIOLOGICAL MODELLING

2.2.1 Growth Modelling

The length of time which a fish takes to grow to harvestable weight – and what that weight is – remains one of the most important tools in developing any aquaculture financial model. The longer the time taken, the more the fixed asset 'cost' of the growing structure has to be apportioned to the crop. Similarly, the more the annual 'overheads' of the business have to be apportioned to the crop. There is also a longer period of funding 'working capital' before first income starts to be achieved, thereby increasing the overall funding package required by the project.

Shorter crop cycles would be theoretically preferable, but sometimes these are not possible because of the need for the individual fish to reach a certain minimum weight acceptable to the market.

Much depends upon the species of fish which is chosen for farming, and different species of fish have different growth rates and different ‘market sizes’ which consumers want. The annual seawater temperature cycle is also important, since fish metabolism is governed by external temperature. However, there is once again a species-specific aspect to this, since different species of fish are adapted for optimum growth rates at different ranges of ambient temperature.

Fish growth rate tends to be exponential rather than linear hence the percentage weight gain over a fixed period of time remains constant as fish become larger. A further level of complexity is encountered when one or other sex of a species of fish becomes sexually mature during the farming period, which can result in a difficult-to-predict decline in the normal pattern of growth during the reproductive period of the year – which can vary from species to species.

There are several mathematical models which can ‘predict’ the likely growth of a fish under different circumstances, all of which have their advantages and disadvantages. This study will utilise a model based upon the so-called Growth Factor 3 or GF3[4]. Put simply, this is a model which, with a single formula, can predict the growth in weight of a fish over a period of time, taking into account the exponential aspect of fish growth and also (importantly) taking account of the prevailing temperature in each modelled period. The author has clear evidence of cases where GF3 models do not truly reflect the reality in the field, but these are usually due to unpredictable outside influences such as feed quality or water quality. In practice GF3 models can give a ‘fair’ prediction of fish performance over time, particularly over an extended time period. Of course this ‘fairness’ can only be truly assessed retrospectively, by field data, but there are now enough data available to validate the model for most fish species one might consider.

A further problem for aquaculture modelling is that in any ‘sibling’ batch of fish (those from the same egg batch), there is a wide range of individual growth rate. This can make modelling difficult because:

- Some fish might reach harvesting weight well before the predictive model for the whole crop would tend to suggest – yet in the real world we would want to be able to start grading out and selling these.
- Some fish take longer to reach harvest weight – and perhaps are so slow-growing that we might need to harvest them at a lower-than-perfect weight, with a lower sales price, simply because they are clogging up the production system

In this study, the core model actually splits every ‘crop’ of fish into 5 equal 20% tranches or sub-crops (by number), and allows a manual assignment of a different GF3 to each sub-crop (based on experience). This gives a much more accurate picture of how an overall crop (or ‘year crop’, or ‘stock’) of fish will perform – and the model can deal with the harvesting at different times on an automatic basis.

2.2.1.1 Single Year Class Production

For any particular farm, which in the case of marine pen farming would be a cluster of pens moored fairly close to one another, there are two fundamental ways of operating the farm. The original farming technique was to keep the farm in continuous production, by stocking new small

[4] See for example: http://www.syndel.com/spawning/sex_on_the_farm_7.html

fish into pens constantly, and harvesting older fish out of other pens on the farm on a constant basis. This technique is still widely practised by rainbow trout producers.

In Atlantic salmon production, it was quickly discovered that this continuous technique led to a build-up of disease organisms on farms, which spread readily from pen to pen. Farmers tried to tackle these problems with therapeutants such as antibiotics, but disease resistance to these quickly developed throughout the industry.

The problem was overcome in two ways. The development of effective vaccines against the most important diseases was an important step forward, but the industry also began to adopt the single year class and fallow method of production[5]. This is achieved by stocking juvenile fish into one farm in the first year, growing all the fish to market size and then harvesting all the fish out of the farm, leaving it empty. Long experience and good scientific evidence shows that only a brief empty or 'fallow' period, perhaps 4 weeks, is enough to break any potential disease and re-infection cycles. After 4 weeks (or longer if desired), the farm can be safely re-stocked with new juvenile fish, to begin the production cycle again. For salmon farming, infestations of the salmon sea louse can also be partially controlled by this technique, although a further refinement of area fallowing has also been developed.

The importance of single year class pen farming to economic modelling of aquaculture projects is self-evident. If the species of fish takes longer than one year to reach market size, and if the project's expectation is to be able to offer fish every year to the market, then more than one farm site will be required. For existing large farming companies, this is not such a critical consideration, since they already have many farms which will be in different stages of production, thus ensuring market-ready product from one or other location at all times.

However, when considering a new aquaculture business in, for example, offshore locations, it is necessary to ensure that the overall project can provide fish to market every year. This study chooses to use a 'clustered six-monthly input' assumption for production. In essence:

- The core model requires an annual production and harvesting of 10,000 tonnes of gutted fish

- Juvenile fish are available from hatcheries all year round, and in this case the model assumes that a crop of fish will be stocked into a discrete 'farm' every six months, and this crop grows through its cycle and eventually yields 5,000 tonnes of product, whereupon it is briefly fallowed (4 weeks minimum) and then re-stocked.

- Each 'six month' farm will be separated from other ones in a cluster, such that they are each distinct epidemiological units. In open waters separation distances could be much less than the 8 km recommended for inshore pen farms.

- However, all the 'six month' farms in the cluster are managed as a single overall farming operation, with shared access to an offshore platform facility and (to some degree) shared access to larger workboats.

The number of 'six month' units in a farm cluster will depend upon the growth and harvesting cycle for the species of fish which is chosen.

It should be noted that Ryan (2004) also makes an assumption about 'single year class' production in his economic modelling for a 10,000 tpa production operation. However, his model assumes that there will be a small inshore nursery site to hold the year one fish, which will then be transferred to a single larger offshore farm for the final year's grow-out. This is a reasonable

[5] See for example: http://www.scotland.gov.uk/library2/doc06/mff-29.htm

approach, but one remains cautious about the implications of moving part-grown fish from inshore to offshore sites, because of cost and also because of fish health implications.

2.2.2 Feed Conversion

This study is concerned with the farming of carnivorous ('piscivorous') species of fish, i.e. those that require to be fed on diets which themselves are based on other seafood components, principally fish meal and fish oil. Such dry pelleted diets are now commonly available for a wide range of cultivated species, and are both nutritionally sophisticated and a very large part of the cost of producing farmed fish.

The main concern is with how efficiently the farmed fish convert this feed into live flesh. There are several ways of measuring this, but this study will focus on feed conversion ratio (FCR). This indicates how much dry pellet is required to produce a unit weight gain in our live fish. So, for example, if the FCR is 1.2:1, it requires 1.2 kg of dry pellet to be offered to the fish in order to achieve a live weight gain of 1 kg.

The FCRs become a little more complex when taking into account the possibility that some of the pellet feed offered might not be eaten by the fish (wastage), and that some of the feed used might be 'lost' to the production of the farm if individual fish subsequently die before harvest, as a result of disease or accident. The picture is further confused when considering a full scale operation, where part-batches of feed might be wasted by accidents in storage or by going out-of-date due to mishap or bad planning. Essentially the comparison is between 'biological' FCR and 'economic' FCR, and the differences can be quite high. The average economic FCR was 19% higher than the biological FCR for the Norwegian, Scottish and Chilean salmon farming industries in 2003 (KPMG, 2005).

The study's model uses a single FCR component which effectively covers all of the above features. When considering FCR in a hypothetical offshore farming situation, one must balance the potential for better performance due to good water quality and low stocking density with the possible difficulty in delivering feed consistently and efficiently.

2.2.3 Feed Cost

Feed cost is a critical variable in the model. Recent studies (KPMG, 2005) suggest that for inshore salmon farming, feed can cost around £660 per tonne delivered to site in the UK, and around £610 per tonne in Norway. Salmon feed contains expensive pigment, which might not be required if modelling for a non-salmonid species. On the other hand, scientific evidence clearly shows that most 'marine' species of fish require a diet with a higher protein and lower oil content than salmon, which probably balances out with the question of pigment cost.

In a separate analysis (not presented here in detail) of vessel operating costs[6], it seems likely that the additional cost of delivering feed to an offshore fish farm in the North Sea might be around £28 per tonne.

An offshore farm in the North Sea could source its feed in Norway just as easily as it could in the UK, and with similar or even lower delivery charges.

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[6] Based on The Fishermen's Handbook 1998 (Seafish); updated diesel fuel costs to 2005; wellboat specifications MV Crear and Salmo Vest; hypothetical offshore farm located 235 nautical miles from Aberdeen.

2.2.4 Mortality

There is always some mortality in farmed fish stocks, whether caused by disease or accidents. The model allows for a linear pattern of mortality throughout different phases of the crop cycle, and can be varied to suit different assumptions. Experience of inshore cage farming suggests that a total survival through the cycle should be more than 75%.

Ryan (2004) suggests that disease and ectoparasite problems might be reduced in offshore farming, due to good water quality conditions. On this basis it would be reasonable to model with an assumption of quite high survival.

The mortality part of the model, combined with the growth prediction and the assumed harvest weight of the fish, provides an essential 'result': the number of juvenile fish which have to be stocked into the farm at the start of each crop cycle. The cost of these can be assumed, based on industry standard figures, or can itself be further modelled based upon some knowledge of the juvenile production system which is in use. In the present model a single juvenile input cost will be assumed, but as it is a model variable we can make different ranges of assumptions during sensitivity testing.

2.3 TECHNICAL MODELLING

2.3.1 Fixed Assets

A sophisticated model, designed for use in a well-understood type of production system, would normally have a rather complex section which identifies and costs all the elements required to build and install the fish farm itself.

The starting point would be the requirement of the maximum biomass of the modelled stock to be held in acceptable stocking density conditions: a relatively easy number to predict from the biological model. This would then suggest how many cubic metres of farm volume is required at maximum stock, and the model would then digress into a section which tries to predict the appropriate cost of: the cages or pens themselves; the mooring systems; the feeding systems; the monitoring equipment; the work vessels; the harvesting equipment; the share of ancillary shore-based equipment; and the costs of having all these elements installed.

Because offshore farming is such a novel and specialised concept, this study prefers to rely on standardised 'per unit volume' costs which have been put forward by experts in this type of technology. Whilst this might seem to be a rather simple approach, it has one major advantage: if all the other assumptions made in the model are considered reasonable, it can iterate backwards from an acceptable financial result to show just how much an offshore fish farm can afford to cost. Thus the fixed asset component becomes one of the key outputs of the model, rather than just one of the input assumptions.

2.3.2 Other Technical Operating Costs

In land based ongrowing or juvenile production systems there would be a requirement to accurately model certain key operating costs. These would include things such as: electricity for water pumping and aeration; oxygen; and buffering chemicals. Modelling these components requires a good understanding of the biology and technology which is involved, and can be quite a complex exercise.

In cage farming (offshore or inshore), nature is providing most of the resources which are needed, such as clean oxygenated water and the removal of fish wastes. Cage farming is therefore left with a lesser number of regular 'operating costs' to model, and these are usually lumped together by industry analysts as ‘miscellaneous operating costs’. Typically, for UK salmon production in inshore systems, these costs amount to around £0.27 per kg of gutted fish produced (KPMG, 2005).

2.4 MODELLING OTHER COSTS

2.4.1 Labour Costs

It is difficult to model labour costs with any high degree of certainty for offshore aquaculture. In the first place there appear to be some problems in marrying reported ‘per kg of production’ labour costs with actual UK wage rates in the inshore sector anyway. In the second place, it is difficult to predict how many tonnes of fish will be produced ‘per person’ in our hypothetical offshore farming environment. Finally, it is also difficult to predict how much higher the wages would have to be to attract workers to the more rigorous offshore environment.

Current productivity is likely to be somewhere in the region of 130 tonnes of salmon produced per employee in inshore aquaculture in Scotland (FRS, 2005). Average salaries in the manufacturing sector are said to be around £1,900 per month (KPMG, 2005). This figure would imply that labour cost to produce 1 kg of (gutted weight) salmon should somewhere in the region of £0.31 per kg, considering that the average crop cycle of salmon is 18 months.

However, this calculation is clearly too simplistic, and does not take account of variable labour input requirements during the different stages of the crop cycle, and the efficient use of staff amongst several farming locations. A recent report suggests that the actual cost of labour to produce salmon in Scotland is £0.14 per kg.

Unfortunately this type of analysis is of limited use for the rather sophisticated model which is being used in the present study. The model considers different species of fish, with quite different growth cycles. A fish which stays in the farm longer clearly requires a longer period of attention by staff than a fish which is harvested more quickly, and it is important to try to reflect this sort of reality.

The model is of necessity going to work at a much higher site production capacity than is commonly seen in inshore farms in Scotland (as a matter of achieving economy of scale), and will be based on the same approach as used by Ryan – an overall cluster of farms producing a total harvested crop of 10,000 tonnes every year.

On this basis we can assume efficiency of scale in terms of labour, and the following core assumptions for the model are suggested:

- 8 staff are required to be (on average) in constant attention on one ‘six month’ farm or on its remote control base, i.e. each member of staff is contributing to the production of 625 tonnes.
- Staff are paid, on average, £40,000 per annum including employers costs.[7]

[7] An estimate based on national salary levels, but also taking into account anecdotal salary levels in the aquaculture sector in Shetland and anecdotal (www) evidence about labourer’s pay rates on offshore platforms. All of the staff will need to be specialists, and several will require advanced diver and boat handling training.

2.4.2 Financial Costs and Depreciation

Typical depreciation rates in aquaculture would be 10% linear per annum, and considering the harshness of the environment there is little justification to change that assumption for offshore farms.

Costs of finance will clearly depend upon the way the entire farming operation is financed. Some loan capital is inevitable, and even if there was a project entirely funded by equity, some allowance for the annual cost of that should be made in order to achieve good accounting standards. The core model will assume a 50% gearing for projects, with four year term loans at a cautious interest rate of 6%.

2.4.3 Cost of Harvesting

The cost of production of aquaculture species can often usefully be quoted as 'edge of farm', i.e. just the basic cost of growing the fish to a point where it is ready to leave the farm on its way to market. However, it is probably more useful to include costs of harvesting, packing and transport to the next stage in the supply chain, since this can give an indication of competitiveness in terms of location of the farming unit. It is probably particularly important to consider this sort of issue when thinking of offshore aquaculture.

A recent estimate of this element of salmon production in Scotland is averaged for the whole industry at around £300 per tonne of (gutted) fish. Exact methodologies vary from company to company, but the use of wellboats to transport live fish from the farms to a central shore-based gutting station has become increasingly common. For some companies this can mean a wellboat trip from a farm on the Western Isles to a packing station on the mainland West Coast – a one-way trip of perhaps 70 nautical miles. They would not have chosen this method if it was not cost-effective, so one could assume that it is no more costly than the average £300 per tonne quoted above.

Taking this chain of logic one step further, one could hypothesise that the additional wellboat journey distance from a 'typical' offshore farm might be an extra 165 nautical miles. Based on the vessel operating budget discussed in Section 2.2.3 and on a wellboat load of 100 tonnes of live fish, for a farm producing 10,000 tonnes per annum, one can estimate the 'extra' harvesting cost at some £58 per tonne of live fish, equivalent to about £62 per tonne of gutted fish.

The model will therefore initially assume a total 'harvesting cost' of £360 per tonne of gutted fish.

2.4.4 Cost of Stock Insurance

Although it is commonly placed within the 'miscellaneous costs' category in other studies, the study's model is able to separately identify the essential cost component of stock insurance. Although some large multi-national companies might tend to self-insure their stocks, it is probably safe to assume that no new aquaculture venture could proceed without the investor having some assurance that the stock was covered by insurance in case of serious loss due to accident or other mishap.

There are several specialised insurance brokers who operate within the aquaculture sector, and a more detailed project proposal would require a specific request for a quotation. However, for modelling purposes one can draw on industry experience, which suggests that a flat rate 3% of stock value would be representative. The model builds this in automatically, and of course deducts this from the separate budget line of 'miscellaneous costs'.

2.5 SPECIES CHOICE

2.5.1 Introduction

There is a wide range of finfish species under cultivation in marine waters around the world, as illustrated in Figure 1. According to the FAO[8] total production in 2003 was over 2 million tonnes.

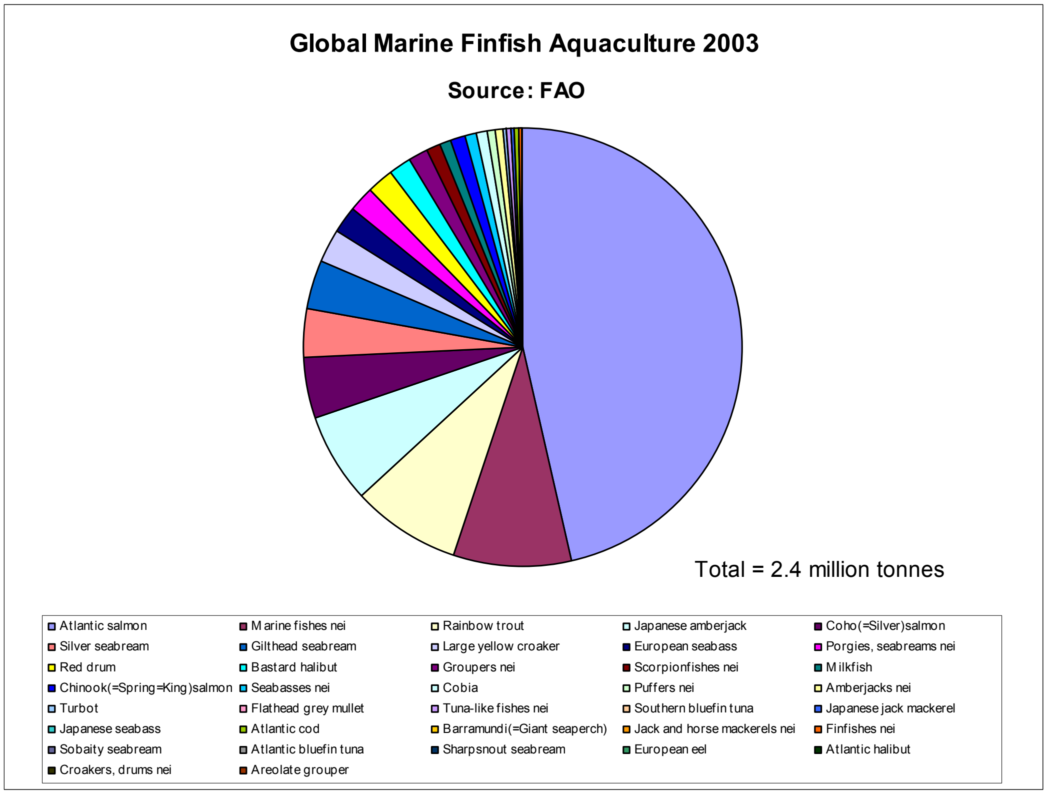

Figure 1 Global Marine Finfish Aquaculture

Production is dominated by salmonid fish, which represent almost 60% of all the production shown in Figure 1. Other families of fish which are well represented are seabass; seabream; and tuna-like fish. Most of the production is round-bodied fish, which would tend to be most appropriate for growing in cages in the sea, whether inshore or offshore.

Another important consideration is the actual market value of marine finfish species that have proved to be durable and successful. Figure 2 illustrates the historical unit value (converted to GBP per kg) of the seven top species which are being farmed on a global basis, and which between them represent some 75% of the total production.

[8] See www.fao.org/fi

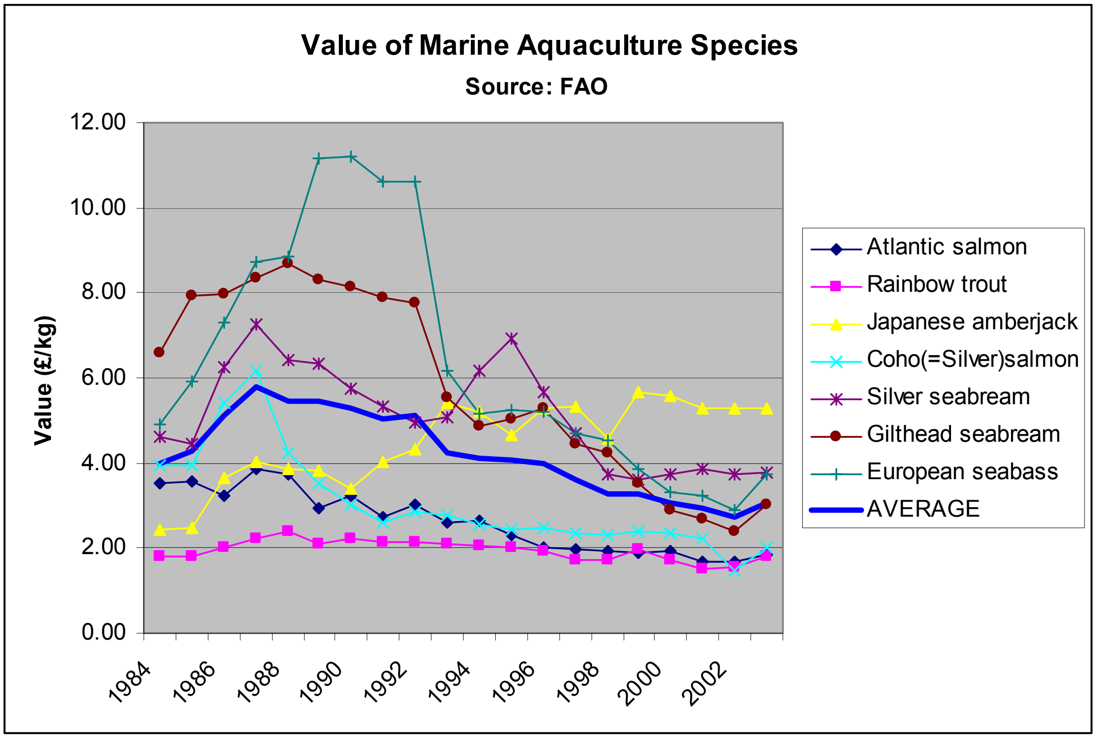

Figure 2 Unit Value of Some Marine Finfish Aquaculture Species

Figure 2 suggests several important points:

- During the early stages of 'domestication' of these species, while learning-curve challenges had to be absorbed by the basic economics of cultivation, the first sale values of these seven species were ranging from £2.00 to over £8.00 per kg.

- Much of the expensive fixed asset investment was being made over the last two decades, and annual depreciation and finance charges were being supported by high sales values.

- Even now, these species have an average first sale value in the region of £3.00 per kg.

- The successful aquaculture species were all 'high value' species (in terms of the wild-caught product) when aquaculture developments commenced.

- Production volume for the seven species grew from 200,000 tpa to almost 1.8 million tpa over the period covered by Figure 2. With the singular exception of Japanese amberjack, the unit value of all of the species went down as production increased.

The present study is concerned with offshore aquaculture in a UK context, and therefore native species which are appropriate for our seawater temperature conditions would be of key interest. However, the offshore oil and gas industry is spread throughout the world, and there is little doubt that if aquaculture was possible in association with such structures, there would be a wider range of candidate species. Of particular interest in warmer waters might be the herbivorous or omnivorous species such as mullets and milkfish, and also the high-value and fast-growing members of the tuna family.

2.5.2 Species Options for UK Waters

We are largely limited to just a few candidate species for offshore aquaculture in association with the oil and gas industry in UK waters. These can be split into two main groups:

- Species for which we have enough information to model their farming

- Species which are of potential interest, but for which there is not enough information available

Although the Market Analysis section of this report addresses market prospects in more detail, it is appropriate to illustrate here in Figure 3 why certain species might be of interest to offshore aquaculture.

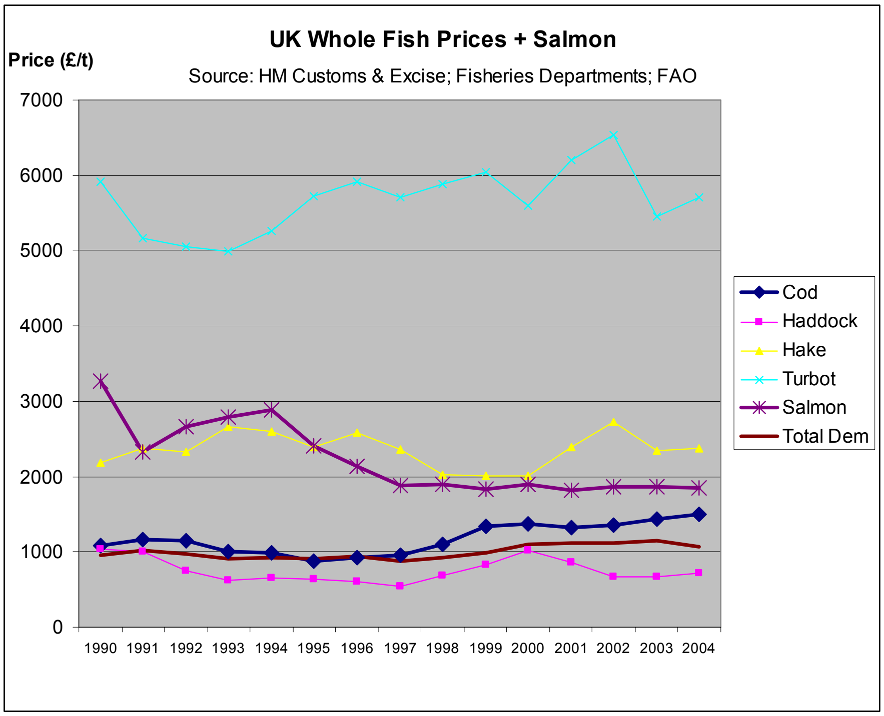

Figure 3 First Sale Values of Some UK Finfish Species

Aquaculture is a business, and the higher the sales value of the end product, the more likely the business is to make profits. Figure 3 suggests several things in this regard:

- Turbot is a successful niche aquaculture species (mainly in Spain), and is making good profits for its investors. As a warm water flatfish species it is not appropriate for offshore UK aquaculture, but is included in the chart because its high value is important to note.

- Salmon farming has been a great success, in the UK as well as elsewhere in the world. Prices[9] have been in decline over many years, and have been hovering just under the £2.00 per kg mark for some time. Critically, when the industry was new and the learning curve was steep (and costly), salmon prices were in the region of £3.00 per kg. Good profits were made by the industry, and equally importantly, unforeseen challenges could be absorbed because margins were so high.

[9] Note: salmon prices in this figure are drawn from the global FAO database for all salmon, not just UK data.

- However, it is worth noting that the salmon farming industry has been in financial difficulty over the period 2001 to 2004, with prices just under the £2.00 per kg mark. Information for 2005 is not yet available, but it is widely recognised that prices have bounced back to levels in the region of £2.60 per kg or more. Farmers are once again making profits, although it may take some time to rebuild balance sheets which have been damaged by the situation over the last 3 years.

- The scarcity of North Sea cod is well documented, and it is clear that cod prices are rising more steeply than the general average for all demersal species. However, the average first price for whole cod in 2004 in the UK was £1.50 per kg. Taken in conjunction with the salmon story outlined above, it seems there are two basic prerequisites for cod farming to succeed in offshore aquaculture:
    - Production costs should really aim to be significantly lower than those for salmon.
    - High value niche markets will need to be found for farmed cod – 'organic' accreditation would be one obvious strategy.

- Hake is included in Figure 3, because it has a market value which is more in line with salmon during 2005, and also because it is a species with a large potential export market outside the UK.[10] Although there is little information available about hake biology, and there would be some lead-time in developing hatchery and basic ongrowing know-how, it may be a worthy candidate for future consideration as an aquaculture species.

- Haddock has been considered as a potential aquaculture species in the UK and Canada, but its market price does not seem to justify further consideration at this time. If anything it is under-indexing on value compared with the average for all demersal species.

2.5.3 Fillet Yield

Ryan (2004) refers to the challenge of farming species of fish with lower fillet yield than others. He quotes the example of cod only yielding 45% edible flesh from a gutted carcass, compared with 60% from salmon. He points out that if input costs are roughly equivalent to produce the whole fish, then the net cost of the fillets to consumers will be higher for cod.

This analysis simply appears to indicate why producers of farmed species such as cod should not contemplate going head-to-head with other animal proteins in retail multiple stores, but should seek high-end foodservice and niche marketing propositions.

Another good example of why one should note, but not become overly concerned about, fillet yield is the history of seabass, seabream and particularly turbot aquaculture. Fillet yields for these species are also low (especially for turbot), yet they have been very successful in aquaculture. Their market niches across Europe have been for whole fish in luxury markets, not filleted product in retail multiples.

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[10] Several industry analysts, the author included, have been interested in the prospects for hake cultivation for many years. Unfortunately there has never been any interest expressed from the traditional aquaculture companies. However, one of the bodies of expert advisers to the Maris Fish Ranch project has recently presented a well-researched paper on the prospects for hake farming.

2.5.4 Modelling for Species in this Study – A Generic Approach

Although a consideration of ‘named’ species choice for offshore aquaculture is important in absolute terms (for the UK, for example), it is perhaps something of a distraction in terms of modelling. A more useful way to approach the modelling exercise, and to make it more useful on a global basis, is to consider two fundamentally different generic ‘types’ of aquaculture species:

Species A: Fast-growing species, for which a full crop cycle can be completed within 2 years.

- A total number of 4 ‘six month’ farming units will be required in the cluster which makes up the overall 10,000 tpa production facility.

Species B: Slower-growing species, for which a full crop cycle requires up to 3 years.

- A total number of 6 ‘six month’ farming units will be required in the cluster which makes up the overall 10,000 tpa production facility.

Growth rate is of fundamental importance to aquaculture economics and in practical terms and defines the amount of time required to cultivate the final product. Practical experience of successful finfish aquaculture on a global basis clearly indicates that generic species differentiation into a 2 or 3 year crop cycle is justified.

There are species which are ongrown to harvest weight within one financial year, of which table size rainbow trout in freshwater aquaculture is the best example. However, it is not considered likely that this experience can be translated to offshore marine pen aquaculture.

2.6 ECONOMIC MODELLING OUTCOMES

There are a range of potential ‘outcomes’ from an economic model, each of which provides different information which might of use to would-be investors. This study will concentrate on three very different outcomes.

2.6.1 Unit Cost of Production

Unit cost of production has been chosen because it is a commonly-used indicator of aquaculture economics. There is therefore the opportunity to compare the results from this study with those published elsewhere.

It is also a useful indicator to chose when considering a ‘generic species’ approach to the modelling exercise. It does not require any assumptions about market price of the species of fish which is being modelled. It does, however, provide recipients of the study with an indication of where they might look for suitable candidate species.

The unit cost of production in this study is defined as the cost of the gutted product, delivered fresh to the first buyer beyond the immediate vicinity of the farm.

In practice this could be the cost of the product brought ashore to the company’s own processing factory, but it could equally apply to the product arriving at the premises of another business.

2.6.2 Internal Rate of Return

This indicator is more strategic, since it brings in the concept of an overall investment package, and its long term implications. It takes account of whether there will be 4 or 6 farms needed for the overall investment (i.e. Species A or Species B). It requires an estimation of market price of the fish, so this is also a parameter in the assumptions part of the model.

The internal rate of return (IRR) used in this model is a numeric indicator of a 10 year discounted cash flow (DCF) analysis of the business. There is no allowance for inflation or corporation tax, and of course finance costs are not typically included in this sort of simple cash flow analysis. The DCF model is based on an initial analysis of the net cash flows of each of the 'six month' farming units, which are then automatically transposed into an annual cash flow projection.

Box 1 Internal Rate of Return

The significance of IRR indicators can be difficult to assess, but in the author's experience start-up aquaculture ventures, particularly where novel technology is involved, require high IRRs if they are to look interesting to investors. Typically IRRs > 30% would be required to interest pure financial investors. Industrial investors already in aquaculture would probably be content with IRRs of 15%+ if the technology was proven, but this is not the case with offshore aquaculture.

See also e.g.:
http://cmsu2.cmsu.edu/public/classes/ejones/Principles%20of%20Finance/chapter%209.

2.6.3 Total Investment Required

The DCF model can also indicate another possible useful outcome: the total investment package required for the entire project. An examination of the net cash flows in early years can suggest how much money has to be invested in the business before positive cash returns commence. In practice this figure is an underestimate, since the DCF model does not include costs of finance charges. Debt capital repayments (interest only, or both interest and capital) in the early years would also have to be factored into the equation. Care should also be taken to accurately predict the cash requirements during the early part of the transitional year into positive cash flow.

It may be possible to obtain debt financing with a 'capital and interest holiday' arrangement for the early years, in which case the DCF model provides a good indication of overall funding requirement. However, in that scenario the additional interest burden is rolled up into subsequent years of the term loan, and it will be important to ascertain whether the Profit and Loss projections for these later years can cope with the higher levels of debt repayment.

2.7 ECONOMIC MODELLING RESULTS

2.7.1 Species 'A' Core Model

Figure 4 illustrates the front page of the basic 'core' economic model for a two-year growth species, i.e. Species A. It shows the cells into which various assumptions can be entered. A sophisticated monthly biological and financial model lies behind this page, but all the key outcomes are reflected back onto this page.

2.7.1.1 Species A - Core Model Assumptions and Growth Projections

Many of the input assumptions have been discussed in the preceding text, but the following points should be noted:

1. All assumptions can be changed in the model in order to study their effect on the outcomes, but sales price, juvenile cost and unit volume cost of the pen structures have been chosen for the initial sensitivity analysis. These boxes are highlighted in purple in Figure 4.
2. Initial sales price assumption is based on our understanding of the current (2005) price of a farmed species such as Atlantic salmon.
3. Initial juvenile cost reflects that of a species which has a fairly long hatchery/nursery production phase, before becoming a 'cage-ready' 75g juvenile.

4. Pen construction cost per unit volume is based on an optimistic appraisal of the various estimates which have been presented by other workers, and discussed elsewhere in this report.
5. Other fixed asset costs are largely based on a pro-rata analysis of the data provided by Ryan (2004).
6. Monthly seawater temperatures are based loosely on prevailing West Coast of Scotland temperatures.
7. The GF3 factors chosen for the core model provide growth rate outcomes which would tend to reflect typical performance of a species that can be completely harvested within 2 years, as illustrated in Figure 4.
8. A flat-rate monthly mortality of 1.5% has been selected, which results in an overall crop survival of 79%. This is reasonable, although in practice there might tend to be a higher level of mortality (but of smaller fish) during the first few months of the ongrowing cycle.
9. The cost of finance is derived from an assumption of 50% gearing, a four-year fixed term loan, with interest at 6% p.a.
10. The model cannot predict or assume the possible additional costs imposed by the challenges of net cleaning, inspections and harvesting in such large offshore pens, but is hoped that these could be accommodated within the cost structures shown in the model.
11. The model does not make any judgement about how many pens there should be, or how large they should be. That would work required from a much more detailed pre-pilot scale project proposal.

MODEL ASSUMPTIONS AND OUTPUTS | **Species A - Modelling Option A1**

ASSUMPTIONS

Annual Temperatures	
Month	**Temp (Deg C)**
JAN	7.2
FEB	6.4
MAR	6.4
APR	6.7
MAY	9
JUN	12
JUL	12.8
AUG	13.4
SEP	12.8
OCT	11.8
NOV	10.8
DEC	8.8

Juvenile Input			
Month		May	
Mean Weight		75	g
Number		1,900,000	
Growth Rate			
Lifetime GF3	Class A	3	
	Class B	2.7	
	Class C	2.4	
	Class D	2	
	Class E	1.7	
Juvenile Cost		1.00	£

Sales Price	
2.50	£/kg
(Delivered, gutted wt)	

Operating Parameters		
Harvest Target Weight	4,000	g
Gutting Loss	7%	
Harvesting, Packing & Transport	360	£/t
Feed Conversion Ratio	1.4	:1
Price of feed delivered	630	£/t
Cost of Stock Insurance	3%	
Number of staff	8	
Monthly cost per staff member	3,333	£
Miscellaneous Costs	40,000	£/month
Monthly mortality	1.50%	%

Fixed Asset Costs			
Maximum permitted Stock Density		15	kg/m3
Cost per m3 of basic cage structures		2.50	£
Feeding Systems	1	1.5	£ mill
Boats & vehicles		0.9	£ mill
Monitoring & robotics		0.75	£ mill
Share of shore & platform bases		0.5	£ mill

OUTCOMES

Tonnes harvested (gutted wt)	5,019	per crop
Survival	79%	
Maximum Biomass	3,408,193	kg
Maximum Volume	227,213	m3
Fixed Asset Cost - One 'Six Month' Farm	**4.22**	£ mill

		Profit/Loss	**Unit Cost**
	£,000s	***£,000s***	***£ per kg***
Sales		12,548	
Feed	4,760		0.95
Labour	507		0.10
Juveniles	1,900		0.38
Harvest, Transport & Packing	1,807		0.36
Gross Margin		3,574	
Stock Insurance	141		0.03
Miscellaneous Operating	800		0.16
Depreciation	703		0.14
Finance (Approx)	638		0.13
Profit before tax		1,293	**2.24**

Internal Rate of Return	**15%**

Estimated Finance Required	**23.5**	£ million
(Excluding interest & capital repayments)		

Figure 4 Species A - Core Model

Figure 5 illustrates how the different sub-crops on any one farm grow and are harvested.

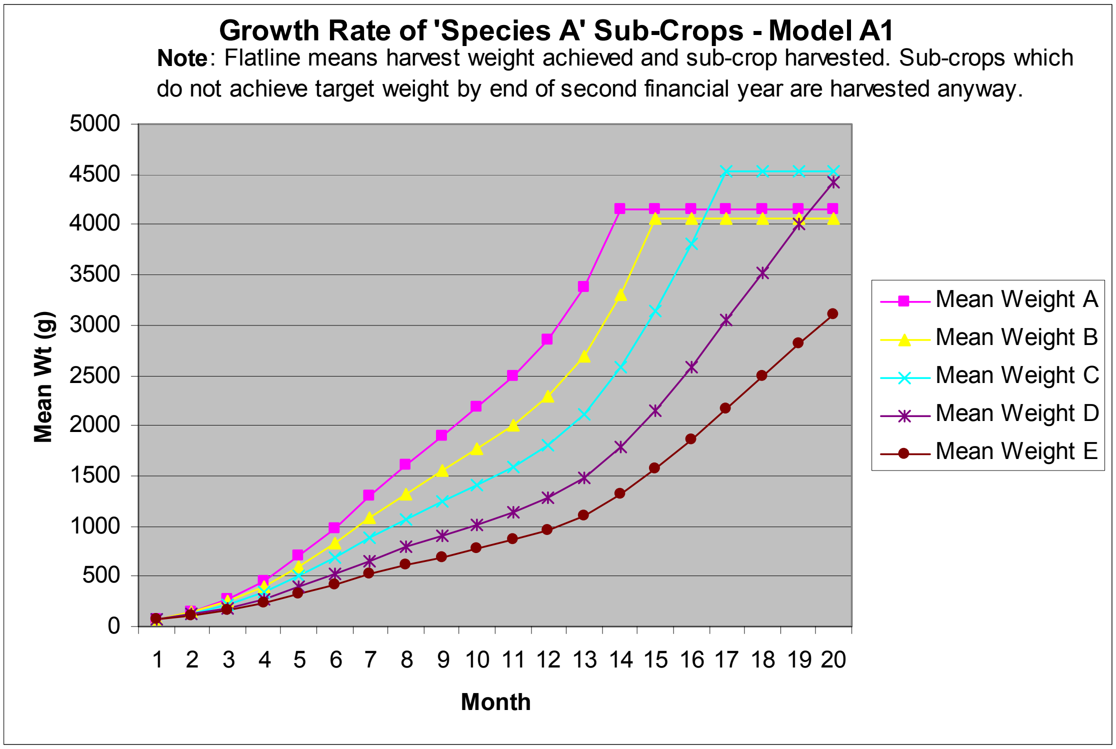


Figure 5 Growth Curves for Species A

2.7.1.2 Species A - Core Model Outcomes

The main outcomes from the Species A core model have been discussed in the preceding text, but the following points should be noted:

1. The unit cost of production from this core Species A model is probably in line with estimates of current Scottish inshore salmon aquaculture.
2. The implications of an IRR outcome of 15% can be considered in the context of Box 1, Section 2.6.2.
3. The model illustrates that would-be investors must consider a total funding package of at least £23.5 million in order to establish this project.

2.7.2 Species 'B' - Core Model

Figure 6 illustrates the front page of the basic 'core' economic model for a three-year growth species, i.e. Species B. It shows the cells into which various assumptions can be entered. A sophisticated monthly biological and financial model lies behind this page, but all the key outcomes are reflected back onto this page.

2.7.2.1 Species 'B' Core - Model Assumptions and Growth Projections

Many of the input assumptions have been discussed in the preceding text, but the following points should be noted:

1. All assumptions can be changed in the model in order to study their effect on the outcomes, but sales price, juvenile cost and unit volume cost of the pen structures have been chosen for the initial sensitivity analysis. These boxes are highlighted in purple in Figure 6
2. Initial sales price assumption is based on the same market price as Species A, but probably also reflects the higher niche market end of the wild-landed prices for some familiar gadoid species.

3. Initial juvenile cost is a relatively optimistic assumption used by one of the other commentators referred to in the preceding text.
4. Pen construction cost per unit volume is based on an optimistic appraisal of the various estimates which have been presented by other workers, and discussed elsewhere in this report.
5. Other fixed asset costs are largely based on a pro-rata analysis of the data provided by Ryan (2004).
6. Monthly seawater temperatures are based loosely on prevailing West Coast of Scotland temperatures.
7. The GF3 factors chosen for the core model provide growth rate outcomes which would tend to reflect typical performance of a species that can be completely harvested within 3 years, as illustrated in Figure 7.
8. A flat-rate monthly mortality of 1.0% has been selected, which results in an overall crop survival of 79%. This is reasonable, although in practice there might tend to be a higher level of mortality (but of smaller fish) during the first few months of the ongrowing cycle.
9. The cost of finance is derived from an assumption of 50% gearing, a four-year fixed term loan, with interest at 6% p.a.
10. The model cannot predict or assume the possible additional costs imposed by the challenges of net cleaning, inspections and harvesting in such large offshore pens, but is hoped that these could be accommodated within the cost structures shown in the model.
11. The model does not make any judgement about how many pens there should be, or how large they should be. That would be work required from a much more detailed pre-pilot scale project proposal.

MODEL ASSUMPTIONS AND OUTPUTS — **Species B - Modelling Option B1**

ASSUMPTIONS

Annual Temperatures	
Month	**Temp (Deg C)**
JAN	7.2
FEB	6.4
MAR	6.4
APR	6.7
MAY	9
JUN	12
JUL	12.8
AUG	13.4
SEP	12.8
OCT	11.8
NOV	10.8
DEC	8.8

Juvenile Input			
Month		May	
Mean Weight		75	g
Number		2,850,000	
Growth Rate			
Lifetime GF3	Class A	1.5	
	Class B	1.4	
	Class C	1.3	
	Class D	1.2	
	Class E	1.1	
Juvenile Cost		0.30	£

Sales Price	
2.50	£/kg
(Delivered, gutted wt)	

Operating Parameters		
Harvest Target Weight	2,500	g
Gutting Loss	7%	
Harvesting, Packing & Transport	360	£/t
Feed Conversion Ratio	1.4	:1
Price of feed delivered	630	£/t
Cost of Stock Insurance	3%	
Number of staff	8	
Monthly cost per staff member	3,333	£
Miscellaneous Costs	40,000	£/month
Monthly mortality	1.00%	%

Fixed Asset Costs			
Maximum permitted Stock Density		15	kg/m3
Cost per m3 of basic cage structures		2.50	£
Feeding Systems	1	1.5	£ mill
Boats & vehicles		0.9	£ mill
Monitoring & robotics		0.75	£ mill
Share of shore & platform bases		0.5	£ mill

OUTCOMES

Tonnes harvested (gutted wt)	5,032	per crop
Survival	79%	
Maximum Biomass	3,958,079	kg
Maximum Volume	263,872	m3
Fixed Asset Cost - One 'Six Month' Farm	**4.31**	£ mill

		Profit/Loss	Unit Cost
	£,000s	*£,000s*	*£ per kg*
Sales		12,580	
Feed	4,772		0.95
Labour	747		0.15
Juveniles	855		0.17
Harvest, Transport & Packing	1,812		0.36
Gross Margin		4,395	
Stock Insurance	132		0.03
Miscellaneous Operating	1,120		0.22
Depreciation	1,006		0.20
Finance (Approx)	691		0.14
Profit before tax		1,446	**2.21**

Internal Rate of Return	**10%**	
Estimated Finance Required (Excluding interest & capital repayments)	**30.7**	£ million

Figure 6 Species B - Core Model

Figure 7 illustrates how the different sub-crops on any one farm grow and are harvested.

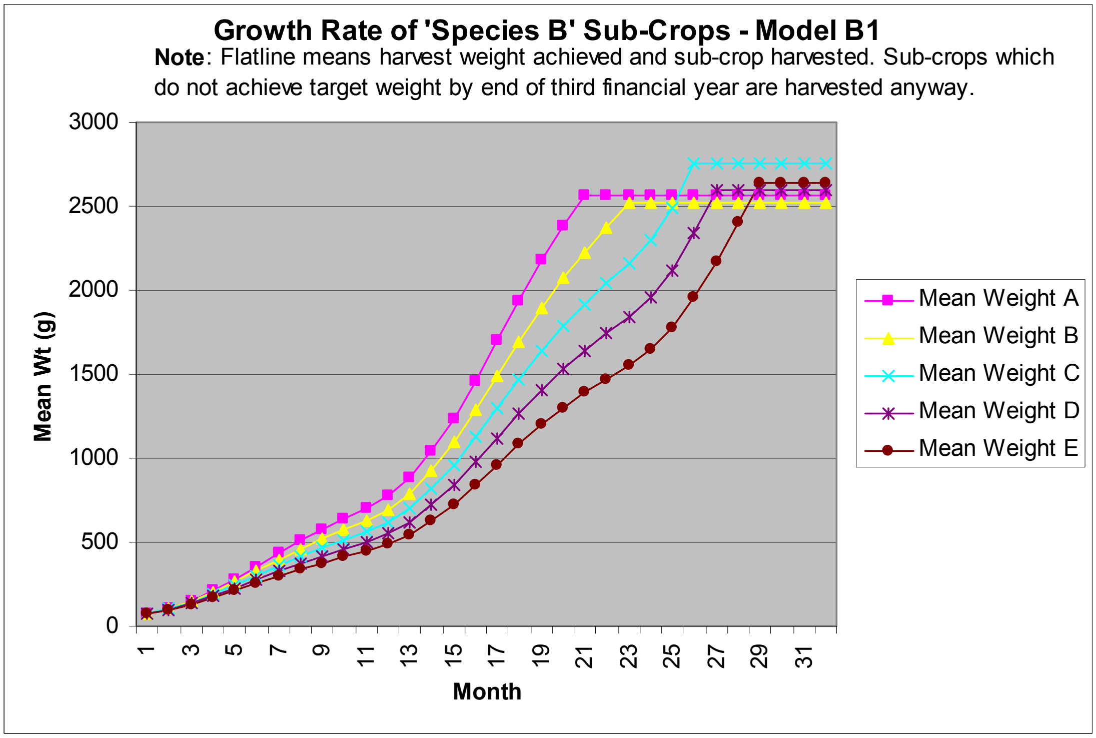


Figure 7 Species B Growth Curves

2.7.2.2 Species 'B' Core Model Outcomes

The main outcomes from the Species B core model have been discussed in the preceding text, but the following points should be noted:

4. The unit cost of production from this core Species B model is probably in line with estimates of current Scottish inshore salmon aquaculture.
5. The implications of an IRR outcome of 10% can be considered in the light of the discussion in Box 1.
6. The model illustrates that would-be investors must consider a total funding package of at least £30.7 million in order to establish this project.

2.7.3 Sensitivity Modelling For Species 'A' and Species 'B'

2.7.3.1 Species 'A' Sensitivity to Sales Price and Pen Cost

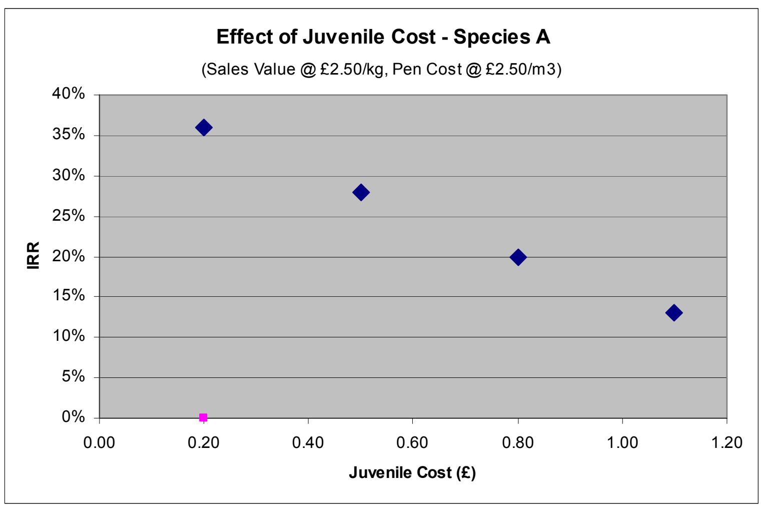
The core Species A model has been subjected to one main series of sensitivity tests, which explore the likely outcomes if sales price and pen costs are modelled over a variety of ranges. Figure 8 illustrates the results of this analysis. The 'core' Species A model is highlighted by the blue border, near the centre of Figure 8.

Species A - Sensitivity Matrix 1 (Fixed Juvenile Cost at £1.00 delivered)

	Sales Value (£/kg)	3.00	2.75	2.50	2.25	2.00	1.75	1.50	1.25	
Cage Cost (£/m3)										
1.00	Production Cost	2.23	2.23	2.23	2.23					£/kg
1.00	IRR	40%	29%	17%	4%					
1.00	Finance Package	18.10	20.10	22.20	24.20					£ mill.
1.50	Production Cost	2.23	2.23	2.23	2.23					£/kg
1.50	IRR	39%	28%	16%	3%					
1.50	Finance Package	18.6	20.6	22.6	24.6					£ mill.
2.00	Production Cost	2.24	2.24	2.24	2.24					£/kg
2.00	IRR	39%	27%	16%	3%					
2.0	Finance Package	19.0	21.2	23.1	25.1					£ mill.
2.50	Production Cost	2.24	2.24	2.24	2.24					£/kg
2.50	IRR	38%	27%	15%	3%					
2.50	Finance Package	19.5	21.5	23.5	25.5					£ mill.
3.00	Production Cost	2.25	2.25	2.25						£/kg
3.00	IRR	37%	26%	15%						
3.0	Finance Package	20.0	22.0	24.0						£ mill.
3.50	Production Cost	2.25	2.25	2.25						£/kg
3.50	IRR	36%	26%	15%						
3.50	Finance Package	20.4	22.4	24.4						£ mill.
4.00	Production Cost	2.25	2.25	2.25						£/kg
4.00	IRR	36%	25%	14%						
4.00	Finance Package	20.9	22.9	24.9						£ mill.
4.50	Production Cost	2.26	2.26	2.26						£/kg
4.50	IRR	35%	25%	14%						
4.50	Finance Package	21.3	23.3	25.3						£ mill.
5.00	Production Cost	2.26	2.26	2.26						£/kg
5.00	IRR	35%	24%	14%						
5.0	Finance Package	21.8	23.8	25.8						£ mill.

Figure 8 Species A Sensitivity Model Matrix 1

Figure 9
Species A IRR Sensitivity to Juvenile Cost



A further shorter analysis was undertaken, considering the effect of varying the juvenile cost around the 'core' model, and considering only the IRR outcomes. This is illustrated in Figure 9

2.7.3.2 Species 'B' Sensitivity to Sales Price and Pen Cost

The core Species B model has been subjected to one main series of sensitivity tests, which explore the likely outcomes if sales price and pen costs are modelled over a variety of ranges. Figure 10 illustrates the results of this analysis. The 'core' Species B model is highlighted by the blue border, near the centre of Figure 10. For Species B, a further full modelling matrix was prepared on the assumption that juvenile fish of 75g were more likely to cost £1.00 at the present time, or in any period where juvenile supply was limited by technology or other factors. This matrix is shown in Figure 11.

Species B - Matrix 1 (Fixed Juvenile Cost at £0.30 delivered)

	Sales Value (£/kg)	3.00	2.75	2.50	2.25	2.00	1.75	1.50	1.25	
Cage Cost (£/m3)										
1.00	Production Cost	2.19	2.19	2.19	2.19					£/kg
1.00	IRR	29%	20%	11%	2%	NEG	NEG	NEG	NEG	
1.0	Finance Package	22.2	25.3	28.3	31.3					£ mill.
1.50	Production Cost	2.2	2.2	2.2	2.2					£/kg
1.50	IRR	28%	20%	11%	1%	NEG	NEG	NEG	NEG	
1.5	Finance Package	23.0	26.1	29.1	32.1					£ mill.
2.00	Production Cost	2.21	2.21	2.21	2.2					£/kg
2.00	IRR	27%	19%	11%	1%	NEG	NEG	NEG	NEG	
2.00	Finance Package	23.8	26.8	29.9	32.9					£ mill.
2.50	Production Cost	2.21	2.21	2.21	2.21					£/kg
2.50	IRR	26%	19%	10%	1%	NEG	NEG	NEG	NEG	
2.50	Finance Package	24.6	27.6	30.7	33.7					£ mill.
3.00	Production Cost	2.22	2.22	2.22	2.22					£/kg
3.00	IRR	26%	18%	10%	0%	NEG	NEG	NEG	NEG	
3.00	Finance Package	25.4	28.4	31.5						£ mill.
3.50	Production Cost	2.22	2.22	2.22						£/kg
3.50	IRR	25%	17%	9%	0%	NEG	NEG	NEG	NEG	
3.50	Finance Package	26.2	29.2	32.2						£ mill.
4.00	Production Cost	2.23	2.23	2.23						£/kg
4.00	IRR	25%	17%	9%	0%	NEG	NEG	NEG	NEG	
4.0	Finance Package	27.0	30.0	33.0						£ mill.
4.50	Production Cost	2.24	2.24	2.24						£/kg
4.50	IRR	24%	16%	8%	0%	NEG	NEG	NEG	NEG	
4.50	Finance Package	27.8	30.8	33.8						£ mill.
5.00	Production Cost	2.24	2.24	2.24						£/kg
5.00	IRR	23%	16%	8%	NEG	NEG	NEG	NEG	NEG	
5.00	Finance Package	28.6	31.6	34.6						£ mill.

Figure 10 Species B Sensitivity Matrix 1

Species B - Matrix 2 (Fixed Juvenile Cost at £1.00 delivered)

	Sales Value (£/kg)	3.00	2.75	2.50	2.25	2.00	1.75	1.50	1.25	
Cage Cost (£/m3)										
1.00	Production Cost	2.61	2.61							£/kg
1.00	IRR	9%	1%	NEG	NEG	NEG	NEG	NEG	NEG	
1.00	Finance Package	34.6	37.7							£ mill.
1.50	Production Cost	2.61	2.61							£/kg
1.50	IRR	9%	1%	NEG	NEG	NEG	NEG	NEG	NEG	
1.50	Finance Package	35.4	38.5							£ mill.
2.00	Production Cost	2.62	2.62							£/kg
2.00	IRR	9%	1%	NEG	NEG	NEG	NEG	NEG	NEG	
2.00	Finance Package	36.2	39.2							£ mill.
2.50	Production Cost	2.63								£/kg
2.50	IRR	8%	0%	NEG	NEG	NEG	NEG	NEG	NEG	
2.5	Finance Package	37.0								£ mill.
3.00	Production Cost	2.63								£/kg
3.00	IRR	8%	0%	NEG	NEG	NEG	NEG	NEG	NEG	
3.00	Finance Package	37.8								£ mill.
3.50	Production Cost	2.64								£/kg
3.50	IRR	8%	0%	NEG	NEG	NEG	NEG	NEG	NEG	
3.50	Finance Package	38.6								£ mill.
4.00	Production Cost	2.65								£/kg
4.00	IRR	7%	0%	NEG	NEG	NEG	NEG	NEG	NEG	
4.00	Finance Package	39.4								£ mill.
4.50	Production Cost	2.65								£/kg
4.50	IRR	7%	0%	NEG	NEG	NEG	NEG	NEG	NEG	
4.50	Finance Package	40.2								£ mill.
5.00	Production Cost	2.66								£/kg
5.00	IRR	7%	NEG	NEG	NEG	NEG	NEG	NEG	NEG	
5.0	Finance Package	41.0								£ mill.

Figure 11 Species B Sensitivity Matrix 2

2.7.4 The Most Important Variables in Modelling

It is clear from Figures 8 to11 that some assumption categories are more important than others in terms of model outcomes. This can be better illustrated by considering several further iterations of one of the models (Species A in this case, but the principle is the same), as shown in Figure 12.

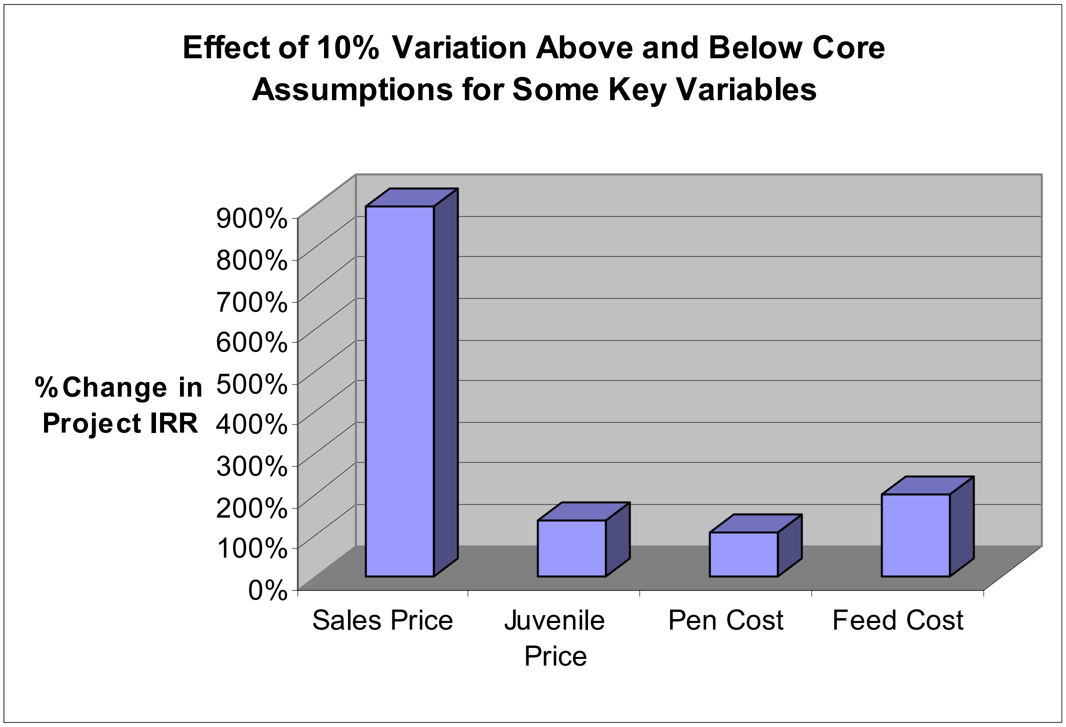


Figure 12 Most Important Variables in Sensitivity Testing

In this case the core Species A model was used, and then varied individually in the categories shown.

Sales price of the final product is by far the most important variable in the model constructed for this project, just as it always proves to be in other aquaculture economic models the author has developed in the past. In the example illustrated in Figure 12, a drop of sales price for Species A, from £2.75 down to £2.25 per kg, reduced the overall project IRR from 27% down to 3%. In essence this sort of perturbation in sales price would turn a ‘good’ investment into a disaster. With total funding of some £20 million or more required upfront, this analysis shows just how important the strength of the marketing plan needs to be.

3. MARKET ANALYSIS IN THE CONTEXT OF OFFSHORE AQUACULTURE

3.1 Introduction

There is a wealth of publicly available information on 'markets' for seafood products, both nationally and internationally[11]. This study focuses on finfish species and will present some of the most recent information from these sources together with unpublished analyses.

When considering the market prospects for aquaculture products produced from offshore sites it is important to bear in mind that they are, to a large extent, entering a well established market place with stringent and high expectations of quality and performance.

Offshore aquaculture production units of a scale of around 10,000 tonnes per annum are unlikely to service small or hard-to-access niche markets and therefore global scale market information (volumes and prices) is appropriate. However, even at a large scale of supply there may be potential to create a positive 'image' for ocean-grown fish, such that it can at least expect to compete at the upper end of any particular market segment.

3.1.1 Defra Data (Also UK Customs & Excise)

Figure 2 (repeated below for clarity) of the Economic Modelling section of the study provides an overview of the recent market price history of some common UK species. This Figure clearly shows the first-sale value trends for some key species that the UK might consider for offshore aquaculture. Of particular note is the fact that Atlantic cod appears to have been over-indexing compared to an average of all demersal species, since the late 1990's.

What Figure 2 does not illustrate is the relationship between volume of supply into the market, and value. This is a particularly important question when considering offshore aquaculture potential, where new additions to the marketplace would be measured in thousands of tonnes per annum.

Figure 13, also from Defra data, permits some analysis of volume and value.

[11] See for example: http://www.seafish.org; www.fao.org
http://statistics.defra.gov.uk/esg/publications/fishstat/default.asp
http://www.scotland.gov.uk/library5/fisheries/sfs04.pdf#search='UK%20Fisheries%20Statistics

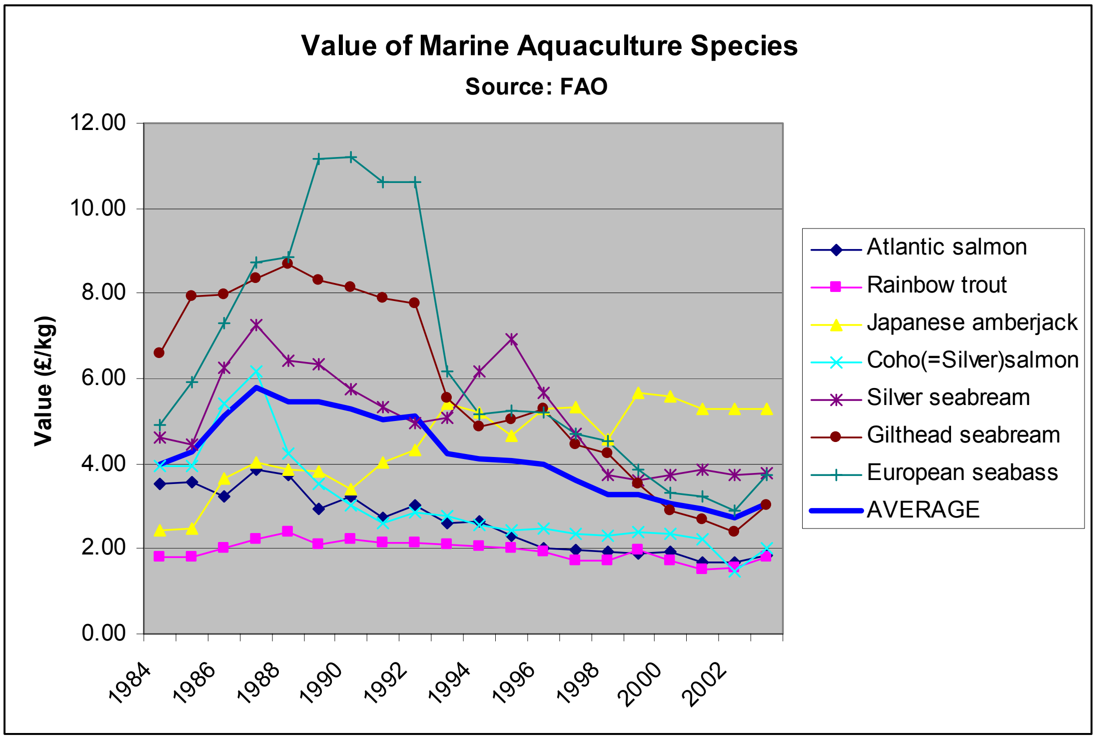


Figure 2 Unit Value of Some Marine Finfish Aquaculture Species

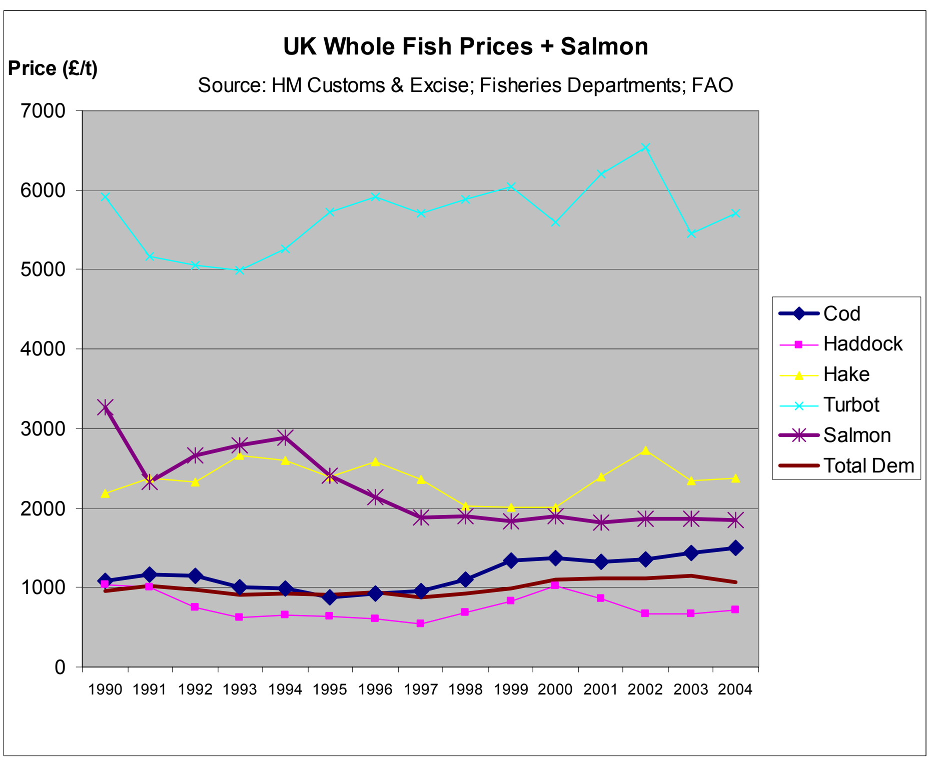


Figure 13 Market Price for Some Key UK Species

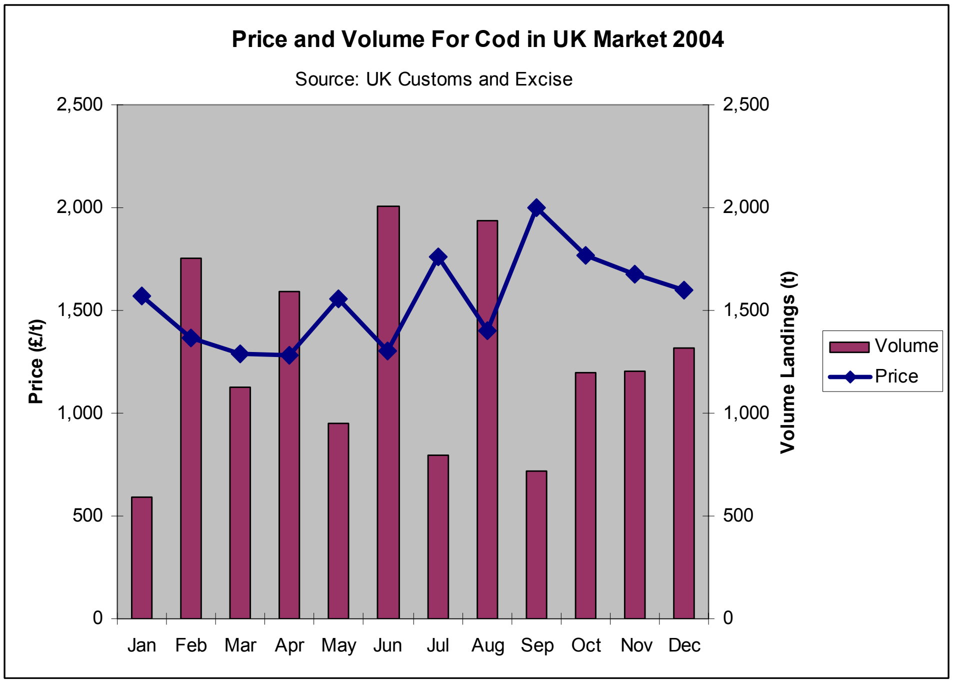


Figure 14 UK Landed Cod by UK Vessels – Volume and Price 2004

Figure 13 might suggest some degree of trend in terms of the first sale value of UK landed cod (by UK vessels), with a tendency for prices to be higher when landings are lower. However, one should remain somewhat cautious about interpreting this in absolute terms: the UK landings in Figure 13 only total 15,000 tonnes, and are a small proportion of the UK cod market in comparison with imported cod (see Figure 14).

Table 3 is part of the database from which Figure 13 was derived, and is reproduced here to illustrate the seasonal volume and value trends for the first half of 2004, for several species.

Table 3 Monthly Landings Summary 2004 (by date of landing)
Quantity, value and average price for landings into UK by UK vessels.

	January			February			March			April			May			June		
	tonnes	£'000s	£s/ tonne	tonnes	£'000s	£s/ tonne	tonnes	£'000s	£s/ tonne	tonnes	£'000s	£s/ tonne	tonnes	£'000s	£s/ tonne	tonnes	£'000s	£s/ tonne
Cod	594	931	1,567	1,752	2,395	1,367	1,130	1,460	1,292	1,591	2,044	1,285	948	1,473	1,554	2,010	2,624	1,306
Dogfish	510	532	1,043	569	499	877	357	404	1,133	387	443	1,147	443	405	913	366	354	967
Haddock	3,540	2,044	577	3,562	2,412	677	3,081	2,498	811	2,138	2,285	1,069	2,756	2,515	913	3,603	2,535	704
Hake	101	238	2,353	84	159	1,881	127	320	2,518	161	437	2,717	216	596	2,752	196	444	2,267
Lemon Sole	133	359	2,695	135	344	2,556	210	602	2,864	226	590	2,610	242	651	2,685	239	536	2,241
Anglerfish	849	1,727	2,035	817	1,548	1,895	1,043	2,241	2,148	1,006	1,831	1,821	1,323	2,433	1,840	1,101	2,182	1,981
Plaice	182	229	1,257	168	156	930	226	262	1,159	240	290	1,209	373	474	1,269	411	540	1,315
Saithe	716	300	419	1,118	491	439	736	308	419	705	279	396	728	312	429	769	323	420
Sole	102	661	6,514	132	831	6,296	149	947	6,369	214	1,598	7,481	178	1,112	6,249	134	815	6,093
Whiting	750	379	506	646	381	590	758	674	889	670	709	1,058	579	508	877	433	297	685
Other Demersal	1,953	2,966	1,519	2,783	3,280	1,179	15,187	4,786	315	14,277	4,608	323	3,400	4,674	1,375	2,694	3,724	1,382
Total Demersal	**9,429**	**10,366**	**1,099**	**11,766**	**12,496**	**1,062**	**23,004**	**14,501**	**630**	**21,614**	**15,115**	**699**	**11,187**	**15,153**	**1,355**	**11,956**	**14,374**	**1,202**
Herring	44	24	553	38	14	365	22	25	1,104	3	1	514	4	3	678	2,197	326	148
Mackerel	37,063	16,350	441	24,046	10,284	428	8,930	3,933	440	341	99	292	65	25	381	52	32	619
Other Pelagic	1,690	270	159	1,323	217	164	831	128	154	68	14	205	8	3	373	10	5	505
Total Pelagic	**38,797**	**16,644**	**429**	**25,407**	**10,515**	**414**	**9,784**	**4,086**	**418**	**411**	**115**	**279**	**77**	**31**	**397**	**2,259**	**363**	**161**
Crabs	981	1,153	1,176	892	1,061	1,190	997	1,277	1,281	1,236	1,491	1,206	1,645	1,806	1,098	1,715	1,827	1,065
Nephrops	1,933	4,685	2,424	2,209	5,461	2,472	2,531	6,050	2,390	2,525	5,676	2,248	2,960	6,753	2,281	3,378	7,408	2,193
Other Shellfish	3,438	4,859	1,413	4,025	5,059	1,257	4,328	5,638	1,303	4,681	5,648	1,206	7,362	6,037	820	6,625	6,064	915
Total Shellfish	**6,351**	**10,697**	**1,684**	**7,126**	**11,581**	**1,625**	**7,856**	**12,966**	**1,650**	**8,442**	**12,814**	**1,518**	**11,967**	**14,596**	**1,220**	**11,718**	**15,299**	**1,306**
Total All species	**54,577**	**37,708**	**691**	**44,299**	**34,592**	**781**	**40,644**	**31,553**	**776**	**30,467**	**28,045**	**920**	**23,231**	**29,779**	**1,282**	**25,932**	**30,037**	**1,158**

Source:- Fisheries Departments in the UK

One of the main messages from Table 3 is that species which have a relatively high value, such as hake or anglerfish (monkfish) are landed in relatively small volumes. The total 2004 hake landings in the UK by UK vessels were only 2,200 tonnes.

Another interesting analysis for a species such as cod can be drawn from the UK Defra database: the relative whole fish equivalent first sale price of cod (port-landed or at point of import), depending upon source, degree of processing and method of preservation. This is illustrated in Figure 14 for the year 2004. It is important to note that the UK Defra core data has been further analysed by the author on the basis that:

- Fillets (or meats) represent an average 36% yield from the whole fish
- Imported or landed whole fish are gutted, with a 15% gutting loss
- Price is therefore quoted as price for whole, un-gutted fish[12]

[12] Modified after Wood (1999) to reflect fillet yield claims from cod aquaculture experience, i.e. a compromise position between skin-on and skin-off fillet yield.

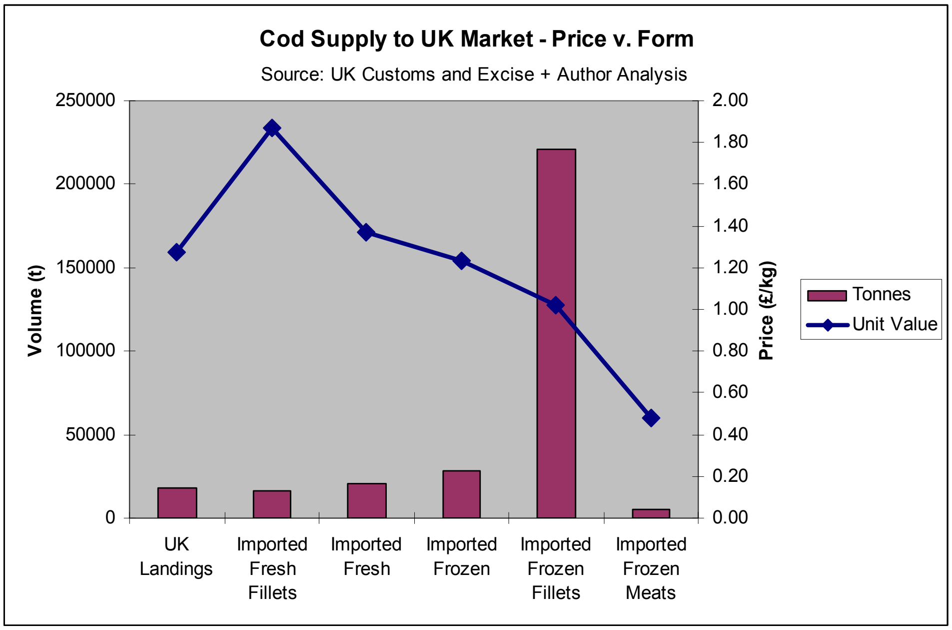


Figure 15 UK Cod Volumes and Prices 2004

The total UK cod supply in 2004 as whole-fish-equivalents amounts to some 309,000 tonnes. The overall average first sale price would be some £1.11 per kg for whole fish. It is worth noting that the author undertook a similar analysis of UK cod supplies in 2001, based upon Defra statistics for the year 2000. This is presented in similar (although not identical) format in Figure 16.

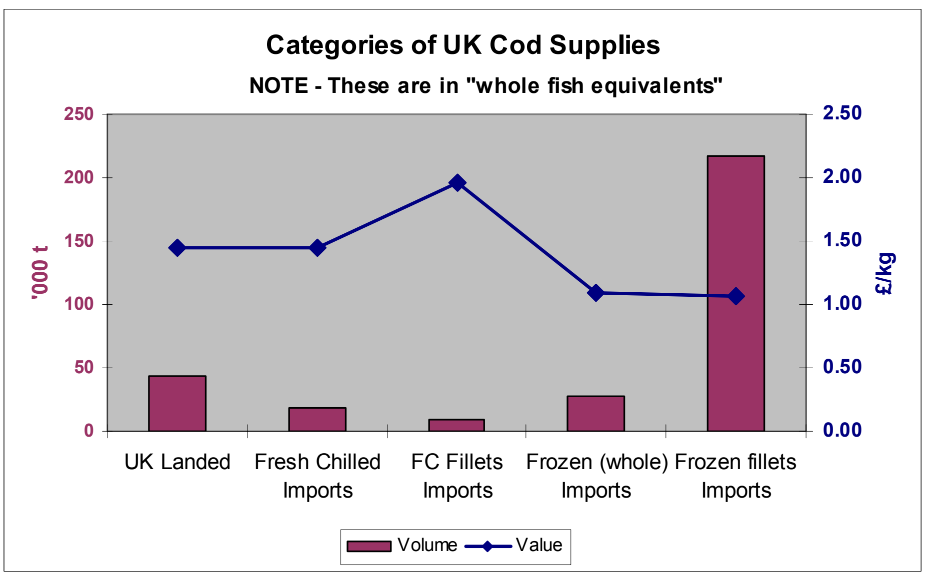


Figure 16 UK Cod Volumes and Prices 2000

The interesting points about a comparison between Figures 15 and 16 are:

- Total whole fish cod supply into the UK market has dropped from 315,000 in 2000 to 309,000 tonnes in 2004

- Overall first sale price has dropped from an average of £1.16 per kg in 2000 to an average of £1.11 per kg in 2004[13]

3.1.2 The FAO Database

Figure 3 in the Economic Modelling section of the study presented one analysis drawn from the extensive FAO database, which provides a comprehensive source of information for any group interested in aquaculture, and it is freely available as a programme and dataset download from the website.

The FAO database clearly indicates that some species of farmed marine finfish are still attaining high prices in international markets. This study is concentrating mainly on the UK potential for offshore aquaculture, and by extension on the UK market for seafood products. However, in a wider global context, the FAO database is a good starting point for considering market prospects for future aquaculture species. The database can also be used to consider trends and opportunities in the UK alone.

3.1.3 EUROFISH

The EUROFISH website[14] is a useful and freely-available source of information on seafood market trends. It regularly presents short but factual analysis of recent trends for certain seafood products, which can vary by region of the world. Cod features regularly, for example in the September 2005 article, one extract from which is shown here.

UK Frozen Cod Fillet Imports
Jan-Jun (tonnes)

	2004	2005	% Change
Denmark	9 400	9 800	+ 4
Iceland	8 400	8 400	-
China	7 900	7 500	- 5
Norway	4 700	4 900	+ 4
Russia	3 400	4 800	+ 41
Faroes	5 400	3 100	- 43
Others	4 600	4 500	- 2
Total	**43 800**	**43 000**	**- 2**

Based on Seafish figures

Figure 17 Example of EUROFISH data

3.1.4 Consumer Spending

One of the best sources of information on UK consumer trends in terms of seafood is Seafish, and an exploration of their website archive is highly recommended. Another source of consumer spending on seafood products is Defra, which provides the information for Table 4.

[13] Although our method of calculation of the raw data is identical for 2000 and 2004, this is such a small difference that a great deal of caution should be built into any interpretation.
[14] http://www.eurofish.dk/

Table 4 Household consumption in United Kingdom

	Consumption (grams)						Expenditure (pence)					
	1998	1999	2000	01/02	02/03	03/04	1998	1999	2000	01/02	02/03	03/04
FISH												
Fresh	31	28	27	32	31	34	17.2	17.3	18.1	21.1	20.3	22.0
Processed and shell	12	14	14	13	13	16	8.6	10.0	11.1	10.1	11.0	13.1
Prepared, including fish products (b)	85	84	82	86	87	91	42.7	43.6	39.6	46.1	46.8	49.8
Frozen, including fish products (b)	20	20	20	26	24	15	10.8	11.6	12.3	15.2	14.9	9.1
Total	**148**	**146**	**144**	**157**	**155**	**156**	**79.3**	**82.5**	**81.1**	**92.7**	**92.8**	**93.9**
MEAT	986	961	1,014	1,032	1,039	1,061	431.1	425.5	443.6	458.3	470.4	492.8
EGGS (number)	1.59	1.54	1.61	1.65	1.66	1.62	15.5	15.6	16.2	16.7	17.2	17.9
CHEESE	103	103	109	112	112	113	51.1	51.7	53.9	56.8	57.9	58.6
ALL FOODS (c)							£16.53	£16.55	£16.96	£17.55	£17.92	£18.38

Source: Expenditure & Food Survey / National Food Survey (Scaled and adjusted for comparison with EFS)

(a) Data are for purchased quantities, per person per week

(b) Changes in the survey mean that it is not possible to differentiate between frozen/unfrozen in some fish products codes

(c) Excludes soft drinks, confectionery and alcohol and consumption outside the home.

Table 4 requires a degree of further analysis in order to indicate trends, but the main summaries would be:

- Seafood consumption as a percentage of household protein consumption as a whole has remained relatively stable over the period 1998 to 2003/4, at around 13-14% by volume and 16-17% by value, although:
- Seafood unit cost per household increased by around 18% over the period
- Meat unit cost per household increased by around 14% over the period
- Overall spend per household increased by 11% over the period

On the basis of Table 4, seafood is at very least holding its own against other food items in household budgets, and yet is costing slightly more. This would appear to be broadly in line with what we might expect from a public that has been increasingly made aware of the value of seafood in a healthy balanced diet.

3.1.5 Store Visits - Retail

Another way to gauge consumer trends is to undertake 'store visits', and try to see what products are on offer to consumers, how they are presented, and what they cost. Various organisations[15] undertake this sort of exercise (and see the Seafish website, for example), but the author has had occasion to do this sort of work directly, albeit on a very small scale. Specifically, comparing prices for certain core seafood products in one of the UK's major retail multiples in late summer 2001 and early 2006:

[15] e.g. Callander McDowell, www.users.zetnet.co.uk/callandermcdowell/relaks175.html

• Fresh MAP[16] cod fillets	£7.99 per kg in 2001	£6.97 per kg in 2006
• Fresh MAP haddock fillets	£8.49 per kg in 2001	£6.58 per kg in 2006
• Salmon fillets	£8.39 per kg in 2001	£6.48 per kg in 2006

This sort of comparison would suggest that the three most important finfish seafood products to UK consumers have come down in price significantly between 2001 and 2006. However, this might be a superficial and potentially misleading analysis. The retail store in question is likely to have changed the mix of ways in which it presents the basic protein source to consumers, offering them more range. For example, in early 2006 the same store is also offering 'skinless, boneless salmon fillets' at £11.08 per kg, and also 'cod loins' at £9.98 per kg.

3.1.6 Port to Shelf Multipliers

It can be interesting to model 'port to shelf' or 'farm to shelf' multipliers, to see if one can detect any trends. This very simple approach requires absolutely no need to understand the complexities of the supply chain between a primary producer and a retail multiple chill cabinet (see Wood, 1999. It does require some basic assumptions about fillet yield and at least one of the primary selling prices. For example:

- If farmed Atlantic salmon sells at £2.50 per kg gutted; its fillet yield is 50%; and its skinless, boneless fillet shelf price to the consumer is £11.08 per kg
    - Then the fillet cost to fillet sales price multiplier is 222%
- If a reverse calculation is undertaken at 222% and 35% fillet yield for cod loins retailing at £9.98 per kg
    - Then the whole fish first sale value could have been £1.58 per kg (i.e. somewhere between the reported first sale value of imported fresh fillets and landed fresh cod – see Figure 3)

It is almost certain that such simplistic analyses contain major sources of error, arising from the fact that the analyst is not privy to the detailed financial operations of the supply chain, or the exact processing and yield information. However, at the same time they provide some degree of generalised overview which is probably justified. What they suggest to any would-be aquaculturist is that certain commercial 'realities' prevail in supplying products to retail multiples, and these are not likely to be deviated-from in any major way.

At this point it should be noted that Greenpeace recently suggested "The total UK retail market for seafood is worth £1.8 billion a year, with nearly 90% of sales made through supermarkets."[17] Other sources of information might be sought, but this statistic seems to be largely in keeping with our understanding of the situation.

With that degree of retail multiple control over the retail market for seafood products in the UK, and with a simple model such as the 'farm to shelf' multiplier to guide would-be aquaculturists, it is clear that large volume production must be carefully focused in terms of production cost and selling price expectation.

On the other hand, if volume expectations are not so high and other species can be chosen for the UK retail sector, then it is interesting to note that in early 2006, the same retail store mentioned earlier was selling:

[16] Modified Atmosphere Pack

[17] http://www.greenpeace.org.uk/contentlookup.cfm?CFID=3503636&CFTOKEN=18994696&ucidparam=20051026155919

- Plaice fillets at £9.27 per kg
- Monkfish fillets at £22.49 per kg
- Halibut fillets at £19.99 per kg
- Large trout fillets at £13.00 per kg

3.1.7 Other Sources of Protein

It is always interesting to consider other protein sources that consumers might choose as an alternative to seafood. In some cases such a choice is no doubt made on the basis of taste, texture or familiarity preference, but price may also become an influencing factor in some situations. A quick overview of other protein products from the same store in early 2006 indicates:

- Chicken Breast Fillets at £6.75 - £8.99 per kg
- Chicken Breast 'Special' at £4.89 per kg
- Turkey Breast at £4.98 per kg
- Beef Sirloin at £10.98 per kg
- Beef quick-fry at £4.88 per kg
- Beef top of range Sirloin at £13.44 per kg
- Lamb Escalops at £11.97 per kg
- Lamb Chops at £8.29 - £9.79 per kg
- Pork Loins at £5.79 per kg
- Pork Chops at £4.88 per kg
- Pork Fillets at £6.63 per kg
- Pork top of range at £6.37 - £8.99 per kg

For volume sales, salmon cod and haddock fillets in the price range £6.50 to £7.00 per kg do appear to be reasonably good value for money in comparison with the other proteins listed above.

3.1.8 Foodservice

Seafood eaten out of the home is an important part of the sector in the UK. Seafish suggested that this market was worth between £25 and £28 billion in 2003, with 20% of all seafood meals being consumed outside the home[18]. The importance of the foodservice sector has also been previously highlighted by the author in other studies (Morgan *et al.*, 2000), and the interesting 'farm to fork' calculator has been introduced as a comparative means of assessing value transfer through the end point of the foodservice supply chain.

In other unpublished work for the British Marine Finfish Association, the author has hypothesised that there is a relatively high-value niche for most large-medium volume species, near the top of the foodservice segment of the market. For a species such as cod, it has been estimated that some 20,000 tonnes per year (whole fish equivalent) might be sold at prices which would have been in line with farmed salmon prices 2-3 years ago. Figure 3 gives an indication of where these might exist, being potential import-substitutes for the high value Icelandic fresh fillets that currently enter the UK market.

The main challenge with the higher-value part of the foodservice sector is 'accessibility'. There are many restaurants and good-food pubs in the UK, requiring high quality seafood products on a consistent basis (and of consistent portion control and price), but these are widely scattered geographically. Typically the ability of aquaculture companies to access this segment of the market has been low to non-existent, with the exception of direct local sales to those outlets near a farm. There are specialised foodservice companies located around the UK that service this

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[18] http://www.seafood.org. Search for "Focus on Foodservice"

segment of the market, and establishing relationships with these is always one possible route for new aquaculture projects to consider.

3.1.9 Distinctive Products

One obvious prospect for any new food production sector must be the idea of branding a product as something distinctive. Organic or similar products might be good examples. A good overview of the general trends in this area can be found in a recent Food Navigator article[19]. The article makes clear reference to a 10-20% increase in anticipated selling price if the effort to achieve the differentiation is successful. This sort of differential could easily be plugged into an economic model of the type developed for this study.

Although there might be some concern about the quality of finfish being farmed near an active offshore production platform due to the chemicals contained in the production waters, this could well be balanced by a positive image of 'open ocean' and 'low density' for farms located near closed installations. There is little doubt, however, that investors would want to see this sort of concept tested on consumers in advance of any investment that relied on the price differential for commercial success.

Whether the price advantage gained is sufficient to meet the profitability requirements of an offshore business plan is a matter of economic modelling, on a case by case basis.

It is clear that for inshore aquaculture projects, this concept of differentiation is already being very successfully applied, in salmon, trout and cod farming. However, volumes of production are realistically limited and farming technology and systems are well understood.

3.1.10 Anglerfish Case Study

Anglerfish (or monkfish) is an interesting species to examine in the light of its apparent retail value - £22.49 per kg.

Wild landings and imports in the UK totalled around 13,200 tonnes of 'whole fish', with an estimated first sale value of around £28.7 million, or an average per kg price of around £2.17 per kg.

Anglerfish have a very poor fillet yield, apparently only some 16% of the whole fish weight by the time the fillets are skinned and trimmed.[20] So it follows that landed 'fillet price' would be £2.17/0.16 per kg = £13.56 per kg. Using the same 'multiplier' as discussed above (222%), we could anticipate the shelf price of anglers or monkfish being some £30 per kg.

In fact they are less expensive than the multiplier for species such as cod and salmon would have us expect. Either the margin-taking through the supply chain is different, or some of the other price information is not quite correct. In any event, it would not seem (even without knowing anything else about their biology) that anglerfish cultivation would be viable, despite the high unit retail price. Low fillet yield and an average first sale value of £2.17 per kg are not particularly attractive combinations.

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[19] http://www.foodnavigator.com/news/news-NG.asp?n=18355-uk-set-for

[20] http://www.practicallyedible.com/edible.nsf/encyclopaedia!openframeset&frame=Right&Src=/edible.nsf/list/Allmouth!opendocument&keyword=Allmouth

3.1.10.1 Volumes In The Market

It is tempting to compare the 'buying pull' of cod (at £6.97 per kg for fillets) with anglerfish (at £22.49 per kg), in relation to how much might be purchased by UK consumers. The reason for considering this sort of comparison would be to hypothesise about how much volume of a fish at an intermediate price might be 'saleable' to UK consumers.

On the basis of landings and imports (see above), and an average main seafood meal portion being around 170 g (a 6 oz. fillet), there might be:

- Some 12.4 million anglerfish 'portions' available to UK consumers each year
- Some 582 million cod 'portions' available to UK consumers each year

Of course not all (by any means) of the cod portions or anglerfish portions are sold to consumers in retail multiples at the unit prices shown above. However, the volume/price comparison is interesting: 47 times more 'units' of cod could be sold at around £7 per kg than anglerfish at around £22 per kg.

It is difficult to take this sort of analysis much further at this stage, without further datasets for intermediate price (and volume) species. Lemon sole and plaice would both be interesting species to model in this regard, as would farmed trout.

Even without undertaking further analysis, it is relatively clear that there will be a strong price/volume relationship for different fish species in the UK market, just as there probably is for different standards of beef products or other proteins.

3.1.11 Imported Fillets

It may be interesting to consider an entirely new paradigm for offshore aquaculture, where it becomes a self-contained source of high quality white fish fillets for 'import' to the UK. Figure 18 illustrates how such products were imported in 2004.

The UK imported 155,000 tonnes of finfish fillets in 2004, with an overall average imported price of £2.58 per kg. Fresh cod fillets achieved a price of £5.19 per kg, whilst frozen cod averaged £2.83 per kg.

The goal for an 'integrated' offshore operation would be to cultivate a fast-growing and high yielding species of fish, and to undertake processing down to fillet level as part of the operation. If that could deliver fillets (fresh or frozen depending upon market niche) as 'imports' to the UK at prices within the regions indicated in Figure 18, then a viable long term business proposition could be considered entirely reasonable. In practice, for North Sea production (considering the outcomes from the economic modelling) this would probably mean a 'Species A' type fish with a market niche price appeal somewhere between fresh cod and frozen anglerfish fillets.

However, it is also important to note that the bulk of imported fish fillets to the UK are in frozen form, with an average value of £2.48 per kg. Frozen seafood product is convenient for consumers, is often of very good quality, and is now a globally-transported commodity. Offshore production undertaken elsewhere in the world, with very different species choices and growing conditions, might well be able to deliver good business results with fillet prices which are more 'mainstream' according to Figure 6. Bearing in mind the high cost of fish feed in the production process, and the global question of fishmeal and oil sustainability, an examination of fast-growing warm water species which are more 'omnivorous' in their nutritional requirements would be interesting.

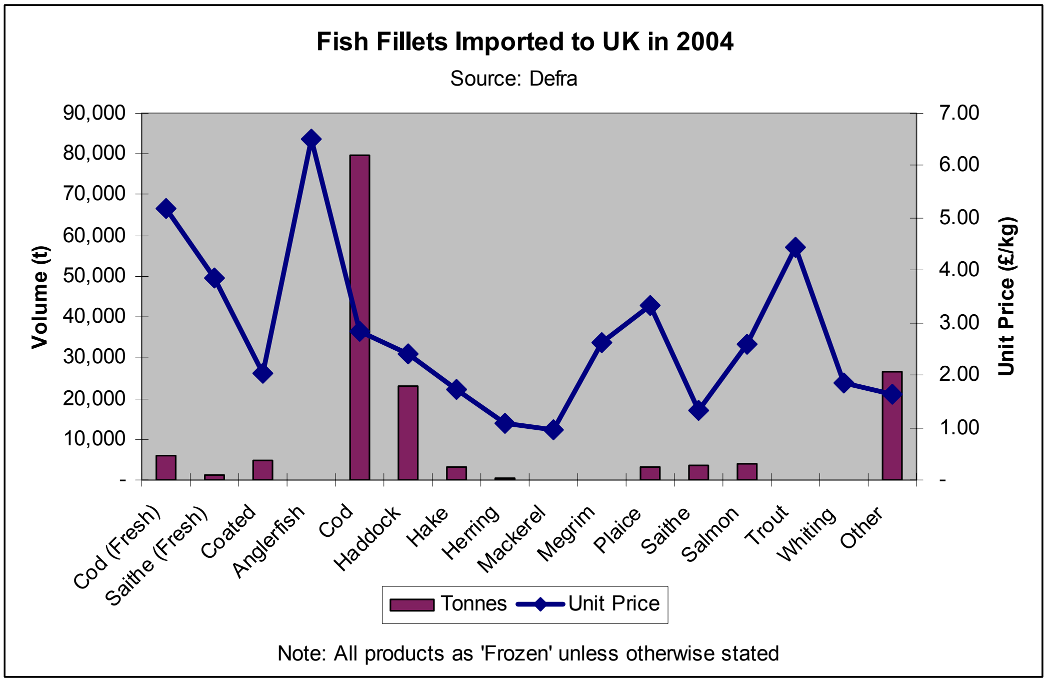

Figure 18 Imported Fillets 2004

3.1.12 Shellfish

This study has concentrated on the economics and market implications of finfish aquaculture in offshore locations. However:

- The author has some quite sophisticated economic modelling tools for a variety of species of shellfish in cultivation, and these could be adapted to take account of possible offshore locations.
- Shellfish prices, particularly for species such as cockles and mussels (which might be amenable to cultivation) have been growing faster on average than finfish prices in the UK market – Figure 19

The modelling work required to consider shellfish cultivation in an offshore location is not inconsiderable, and is out-with the scope of this present study. However, bearing in mind the growth in shellfish consumption in the UK and especially more widely in Europe, further work on this might be justified in the future. Inshore shellfish cultivation is facing many of the same ‘scale up’ pressures and challenges as inshore finfish farming, and new production prospects might be valuable.

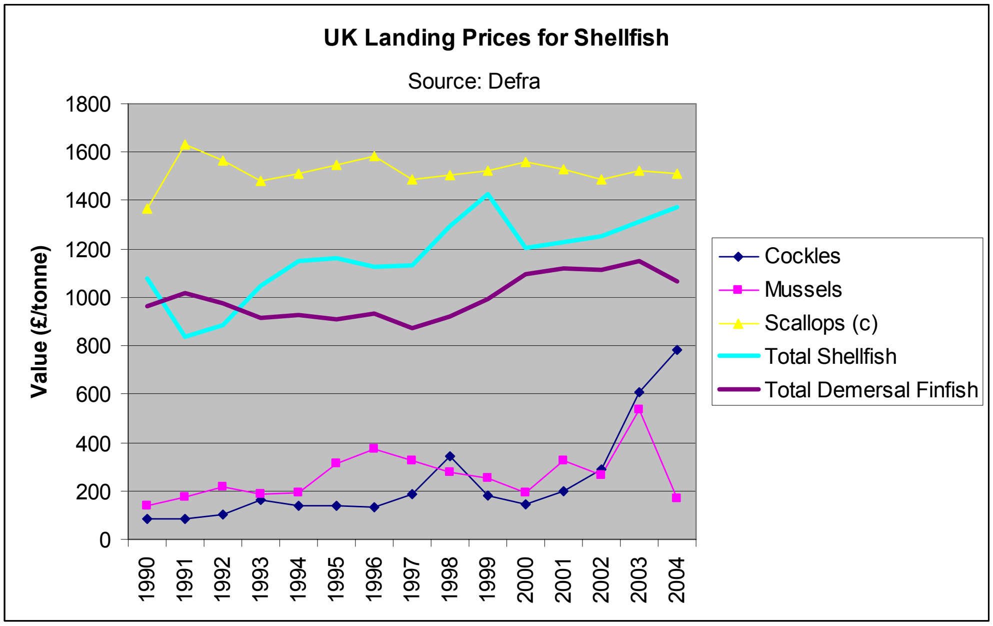

Figure 19 Shellfish Price Trends in UK

4. ECOLOGICAL CONSIDERATIONS

4.1.1 General ecological considerations

The environmental impacts associated with sea-cage (or enclosure) aquaculture have been scrutinised in some detail and there is a substantial literature associated with this subject (see Black, 2001; Beveridge, 2004; Anon, 2004a and b; Benetti et al., 2006). Whilst the process of improving our capacity to understand and model the impacts of aquaculture continues to evolve, particularly in terms of assessing environmental carrying capacity, there are some broad observations which need to be considered in terms of offshore finfish aquaculture development.

There is a general prescription against the culture of non-native species (see FAO, 1995 and ICES WGEIM reports for example) and there is concern over the risks which may be associated with the cultivation of new species i.e. species which may be native, but are to be developed for cultivation. Cultivated species are usually produced in hatcheries from captive broodstock and on-grown in volumes and at stocking densities which are at variance with their occurrence in the wild. There are potential risks associated with interactions between wild and farmed fish, either through competition for resources (food/habitat/mates), disease transfer and genetic dilution. The fate of waste feed, faecal material, diffuse waste and chemical treatments needs to be carefully considered. Interactions with predators will need to be addressed also. Offshore farms will require infrastructure for maintenance and personnel to remain at sea, perhaps for extended periods. Although clear precedents exist for such structures and activities in the offshore oil and gas production sectors and some fishing sectors, the potential environmental impacts will still need to be considered.

In a broader context, the sustainability of aquaculture as a process is increasingly receiving critical attention, particularly with respect to fish meal and fish oil supplies used in carnivorous fish feeds. The scale of some proposed offshore facilities (10,000 tonnes units) could have a significant impact on domestic demand for feed supplies.

As discussed in Section 5, inshore aquaculture is covered by a raft of stringent environmental legislation and regulation, but there are legal anomalies that may, in principle, permit aquaculture activities to be conducted beyond the 3nm and 12nm limits to less rigorous environmental standards than apply inshore. However, it would be naive to imagine that these considerations can be ignored simply on the assumption that they will not be significant in the offshore environment. At present, there is little direct scientific evidence to support this contention. The history of aquaculture inshore suggests that those wishing to develop offshore sites will be subject to a highly precautionary approach to environmental issues and that this should be acknowledged in the overall development plan for such ventures. Many of the principles, practices and regulations pertinent to inshore aquaculture in Scotland for example (see http://www.scotland.gov.uk/library2/doc06/mff-26.htm - March 2006) could potentially be transposed and or modified to address environmental concerns offshore. It would seem likely that before offshore aquaculture proceeds on a commercial scale that an appropriate environmental regulatory framework would have to be established. The Scottish Environment Protection Agency (SEPA) for example would not have a remit to regulate discharges from aquaculture facilities beyond the 3nm limit (D. Sinclair, pers. comm.).

4.1.1.1 Risk Assessment

In 2005 the ICES Working Group on Environmental Interactions in Mariculture (ICES WGEIM, 2005) formally considered the use of Risk Analysis and applying this process to environmental interactions of aquaculture. There is every reason to suspect that a similar process could be applied to the development of offshore aquaculture. A range of qualitative and quantitative criteria would be used within a framework of probability to provide tangible measures of risk for a variety of scenarios relevant to the cultivation of fish offshore. There is a general presumption that prevailing currents, considerable water exchange and great depth will mitigate the impact of cage aquaculture offshore. There are now sophisticated models capable of predicting the fate of discharges from cages, but many have been developed for use in inshore or fjordic systems. Further modification and verification of these models may be required if they are to be applied to the offshore environment. For some of the larger enclosures proposed for lower density fish production (see Section 6), it may be necessary to model the fate of discharges within these systems to assess the impact on the stock itself.

4.1.2 Discharges

It is assumed that the hydrodynamics of the offshore environment will promote better water exchange within cages, facilitating more rapid dispersion of waste. Observations of the wave climate, consequential forces and, moreover, the capacity of the captive stock to survive in such conditions, would suggest that fish (such as salmon and cod) will still need to be cultivated in conditions where current speeds and wave motion is fairly limited. On this basis, the notion that dispersal of waste will be more rapid may need to be examined. What is not in dispute, however, is that the capacity of the receiving water body will permit much greater diffusion of waste materials and that within reason these may be regarded as negligible. However, in the immediate vicinity of the cages, the environmental load is likely to be qualitatively and quantitatively, at least equivalent to inshore cage farming systems.

It would be wrong to assume that offshore farming will simply be an analogue of inshore practice. To offset the significant additional costs of operating offshore, massive economies of scale may be required. Farms producing 10,000 tonnes of fish per year are proposed which, even at low stocking densities (~10kgm^{-3}) would be delivering significant quantities of waste materials into a relatively small area. In line with general environmental policy in this area, it would be for the prospective operator to prove that their activities were not environmentally detrimental.

4.1.3 Solid waste

The principal environmental concern inshore was, for many years, the effect of solid waste from fish cages. Uneaten food and faecal material can impact locally on sediments, smothering the benthos and causing conditions to become anoxic. However, there is evidence that such impacts are relatively non-toxic and reversible (see Black, 2001).

The salient difference between offshore versus inshore systems relates to reduced benthic deposition. Offshore cage systems are likely to be deployed in relatively deep water (*circa* 100m plus), and many may use mooring systems which permit cages to move over a wide area (see Section 6, page 98). Waste loadings per unit area of seabed are therefore likely to be significantly lower than experienced at inshore sites and it is possible that such impacts will not be measurable in terms of biodiversity indices.

There are a number of models such as DEPOMOD[21] (Cromey *et al.*, 2002) and more recently AutoDEPOMOD (http://www.sepa.org.uk/news/releases/view.asp?id=224 – March 2006), used

[21] DEPOMOD is a model used to predict the solids deposition and associated benthic impact from marine cage farms. The model has a modest distribution with over 70 licensed users worldwide in Europe, Canada, Australia, Chile and South Korea and a helpline receives around 100 enquiries per year. After the initial release of DEPOMOD in 1999, the model was further developed to incorporate prediction of sea lice chemical treatment dispersion in 2002. A method was developed by Scottish Environment Protection Agency (SEPA) and SAMS for consenting of sea lice treatments for Scottish salmon farms and AUTODEPOMOD was created. This software incorporates DEPOMOD in the background with additional tools used in the site assessment and allowed streamlining of the whole application process (http://www.sams.ac.uk/research/coastal%20imapcts/depomod.htm - March 2006)

by SEPA to predict the effects of fish farms on the environment and determine where monitoring around sites should take place. These models are also used for setting the limits on the maximum amount of fish a farmer can keep in cages (the biomass).

The AutoDEPOMOD model is capable of predicting concentrations of in-feed medicine residues in the sediments beneath fish farm sites. The comparison of predicted residual concentrations with Environmental Quality Standards (EQS), for the compound in question over an Allowable Zone of Effects (AZE) is used to drive the consenting process for each medicine currently available.

However, many of the parameters used to drive these models will need to be reconsidered for use offshore, if discharges are to be properly regulated. The EU ECASA (Ecosystem Approach to Sustainable Aquaculture) project seeks to bring together current understanding of indicators of ecosystem change both caused by and affecting a wide range of mariculture activities in Europe (http://www.ecasa.org.uk – March 2006). One of the outputs of this project will be a “toolpack” of models and indicators, including appropriate decision support tools to guide aquaculture development. Some of these approaches may be relevant to future offshore aquaculture developments.

4.1.4 Soluble waste

Waste nutrient discharges from cage aquaculture can be substantial both locally and regionally (Beveridge, 2004) and there is concern that enhanced nitrogen and other chemical loadings could change the nature and composition of phytoplankton and microbial communities.

Seawater contains a host of microbial organisms from autotrophic cyanobacteria, diatoms and flagellates to heterotrophic bacteria, flagellates, ciliates and other protozoa. The mix of species occurring at any one location and time are thought to depend largely on the nutrient status of the water. Whilst the gross effects of increased nutrient levels are generally well known, there are few data on less drastic but potentially important effects resulting from changes in the balance between various nutrients. Observations of enhanced bacterial production in the vicinity of fish farms presumably result from increased organic loading. However, it is not known how such organic inputs affect bacterial community composition (i.e. whether activity is enhanced over a wide range of bacterioplankton taxa or only a few individual groups) (http://www.sams.ac.uk/research/pelagic/Microbialcommunities.htm).

Whilst there is no conclusive field evidence to link aquaculture with the development of toxic algal blooms, there is experimental evidence to suggest that some of the soluble waste products discharged from fish farms could potentially trigger toxin production in marine dinoflagellates (for example: Nishimura, 1982; Roberts *et al*., 1983; Graneli *et al*., 1993). Tett and Edwards (2002), compare Lochs Creran and Striven in Scotland and suggest that increased nutrient inputs increase the size of algal blooms and the probability of harmful effects from algae such as *Gyrodinium aureolum* and *'flagellate X'*. Their study shows that hydrographic and other factors are important in controlling the balance of organisms. On a wider scale, the authors suggest that nutrient enrichment does not automatically lead to greater shellfish intoxication.

If the offshore environment utilised by the farm is considered to be relatively nutrient poor, compared to inshore areas, the relative impact of nutrient discharges from the farm may potentially be greater (see for example: http://ciceet.unh.edu/transfer/GOMNutriMgtWhitepaper1.pdf - March 2006).

The use of chemotherapeutants either as bath treatments or as in-feed compounds continues to be the subject of research effort to minimise their use. Inshore, Environmental Quality Objectives (EQO) and Environmental Quality Standards (EQS) are required to be established for chemical discharges which may be of concern. Use of these substances offshore should be effectively regulated also.

4.1.5 Physical changes to habitats

The potential for significant changes to the benthic habitat local to offshore fish farms would seem to be minimal – given great depth and a favourable current regime. However, in quiescent conditions, or at sites where cages might be submerged to depths of several tens of metres for prolonged periods, this assumption may not hold. In the later case, the depth beneath the cages may not be more than is experienced in some deeper inshore sites.

It is likely that offshore cages, enclosures and associated infrastructure will act as "fish attracting devices". In some respects, the presence of wild fish close to the farm could be seen as advantageous as they would consume some of the particulate material escaping from the cage and further reduce its impact within the vicinity of the farm. Alternatively, this could be seen as a negative impact by modifying the behaviour of pelagic fish and inducing consequent changes in biological conditions such as predatory pressure (CITES WGEIM, 2002).

4.1.6 Escapes

Escapes are an inevitable consequence during routine cage culture operations such as stocking, grading and harvesting. Some species of fish including cod are known to chew nets. Occasional mass releases of stock can occur through net damage or other cage structure failures as a result of storms, accidental damage, vandalism, predators and the fish themselves (for example: Webb and Youngson 1992; Youngson *et al.*, 2001; Benetti et al., 2006).

Increasing information is being collated on the scale of escapes and in Scotland and Norway reporting of escape incidents is mandatory. Recent records from Scotland suggest that around 10 to 20 incidents occur per annum, the most common causes being damage by storms or predators, resulting in the release of between 50,000 and 100,000 fish per year (FRS 2002b) – such figures do not take into account the regular operational losses.

Arguments with respect to the impact of Atlantic salmon escapes are well rehearsed. There is concern over the relative size of the wild and farmed populations, with the number of escaped salmon representing a significant relative proportion of the total "wild" population - a fact which could have significant implications for a species in which genetically distinct, non-interbreeding populations occur. There is a general consensus that more needs to be done to minimise escapes of farmed fish and, with respect to salmon, the North Atlantic Salmon Conservation Organisation (NASCO) adopted a resolution in 1994 which has led to the development of industry Codes of Practice in Scotland for example which through cage design standards, guidance or surveillance, and contingency planning, should reduce escapes. There is evidence suggesting that significant escapes are a continuing problem and more work is required (Beveridge, 2004).

The release of large numbers of fish of native species, whilst posing less risk of habitat modification and inter-specific interactions, may aggravate risks to indigenous strains through the introduction of non-adaptive genes with consequent reductions in fitness. There is no evidence that commercially cultured aquatic organisms have novel alleles[22] otherwise absent from wild populations of the same species. Differences in allelic frequencies have been noted. The effect of integration is likely to be proportional to the relative number of wild and cultured organisms interbreeding. Where relatively large scale genetic integration has occurred, there has been reduced fitness and survival of the wild population. Where studied, hybrids of single interbreeding events rapidly disappear from the wild population and the effect is likely to be reversible through natural selection over a period of a few years. Where large scale repeated escapes occur (or

[22] Alternative forms of a genetic characteristic.

releases associated with attempts to restore or enhance stocks), the effects are likely to be larger and the consequences unpredictable (CITES WGEIM, 2005; McGinnity et al., 2003).

Some argue that only “local” stocks should be cultivated, but this is generally impractical, flies in the face of the need to improve farmed strains through genetic selection and ignores the inevitable artifice of selection that will occur as a result of culturing stock in a hatchery environment. The early rearing process will inevitably results in various selection pressures which would not normally be experienced in the wild, thus reducing heterozygosity[23] within a few generations. Whilst farming sterile fish may be an option, this would not solve the problems caused by large scale releases in terms of competitive interactions for food and habitat for example (Benfey, 2001; Beveridge, 2001; Youngson *et al.*, 2001).

The ICES Working Group on the Environmental Impact of Mariculture (CITES WGEIM, 2004) noted that sea bass stocks are divided into highly localized populations and the use of the local strain for culture purposes is to be recommended until more robust containment technologies dramatically reduce the probability of escapes occurring. Recent work on cod suggests that there is evidence of temperature dependent growth differences between stocks on the East and West coasts of Scotland (M. Perutz, pers. comm.) and potentially distinct populations (Wright *et al.*, 2006). The culture and inadvertent release of large numbers of cod should therefore be viewed with similar caution as has been expressed for salmon and sea bass.

One possible advantage of offshore production could be to reduce the interaction between wild inshore populations and stock farmed offshore. But the severity of the conditions likely to be experienced in the offshore environment, coupled with the sizes of cages and stock numbers required to achieve the economies of scale for economic production, would suggest that considerable effort to minimise escapes will be needed. In order to retrieve escaped stock by netting, there may be a requirement for legal derogations to allow for this practice outwith the 12nm limit (See Section 5, page 63).

4.1.7 Disease transfer

It is important to recognise that cultivating fish in offshore conditions is novel and there will be a need to assess the risks of disease transfer between wild and farmed fish in this environment. Wild fish can be a reservoir of infection for cultivated stocks and in reverse farmed stock could potentially infect wild stocks.

In response to concerns about disease transfer and control, the World Trade Organisation accepts the risk analysis protocols developed by the Office International des Epizootic (OIE) as the basis for justifying trade restricting regulatory actions including restriction on movement of commercial and non-commercial aquatic animals. The intent of developing the OIE protocols was to provide guidelines and principles for conducting transparent, objective and defensible risk analyses for international trade. The International Council for the Exploration of the Sea *(*ICES) has embraced this approach in their latest (2003) Code of Practice for the Introduction and Transfer of Marine Organisms. Part of this Code is specifically designed to address the “ecological and environmental impacts of introduced and transferred species that may escape the confines of cultivation and become established in the receiving environment” (CITES WGEIM, 2005).

The epidemiology of many fish diseases is still poorly understood, and cultivating fish offshore may present new challenges. Some of the proposed offshore cages or enclosures would not be well suited to disease containment and control. Inshore, it is generally accepted that fish year classes are separated as part of the disease management strategy. It is not clear whether this has been properly considered in some offshore farm designs.

[23] Genetic variability among individuals within populations and variability among populations.

There is little published scientific evidence to support the claim that offshore fish farms will be less prone to disease. There may be potential advantages for example, if fish hosts such as cod were effectively removed from shallow water parasites such as *Cryptocotyle* sp. However, for sea lice this would not necessarily be true as oceanic salmon will naturally carry sea lice (I. Bricknell, pers comm.). Although indications from Irish salmon farms in exposed locations (Ryan, 2004) and "organic" low density farms off the west coast of Scotland, suggest that reduced levels of sealice may be possible. For bacterial and viral pathogens, this premise has not been well tested and it may be that there are just as many of these pathogens available in the open ocean. Alternatively, if the offshore environment is pristine with respect to some fish pathogens it could potentially be contaminated by their introduction via infected fish from the coastal zone (I. Bricknell, pers comm.).

Kent *et al.*, (1998) conducted a survey of salmonid pathogens in wild fish in proximity to fish farms in British Columbia, revealing a range of pathogens including Viral hemorrhagic septicemia virus (VHS), Infectious hematopoietic necrosis (IHN) virus, *Renibacterium salmoninarum*, the cause of Bacterial Kidney Disease (BKD) and *Aeromonas salmonicida* subsp. *Salmonicida,* the cause of Furunculosis. Fisheries Research Services have conducted similar studies related to cod culture in the UK but this work has yet to be published (I. Bricknell, pers comm.).

Whilst the sites studied could not be defined as "offshore" in the context of this report, it is clear that wild fish can be an effective reservoir of pathogens. Moreover, it is inevitable that wild fish populations will be attracted to offshore fish farms through feeding opportunities and the natural tendency of some species to gather around submerged structures.

4.1.8 Assimilative capacity

The trend is towards whole-system environmental assessment, including considerations of the assimilative capacity of specific systems and their ability to absorb and dilute perturbations (Fernandes *et al.*, 2001). Understanding the assimilative or carrying capacity of the environment has become a key concern for aquaculture development in the UK and elsewhere. Whilst some environmental capacity models – such as those mentioned above, can provide a partial picture of environmental impact, there is a need to incorporate a wider range of parameters, if we are to understand regional and ecosystem changes. More comprehensive assimilative capacity models are under development that take into account wider impacts on the water column together with salient biological terms such as infection rates and other disease factors. In some cases even aesthetic, amenity and other social factors are being included in the concept of environmental capacity (see Beveridge, 2004; CITES WGEIM, 2005). As yet, only Norway has considered assimilative capacity on a national basis for its coastal waters through the LENKA programme (Kryvi *et al.*, 1991). It is likely that any large scale plans to develop offshore aquaculture would need to be included in more general assessments of assimilative capacity.

4.1.9 Feed sustainability

The sustainability of aquaculture and, in particular, the sustainability of fishmeal and fish oil supplies for carnivorous fish feed has been the subject of much debate and it is beyond the scope of this report to address this issue in any detail. However, the proposed scale of offshore aquaculture will inevitably stimulate further debate and the following observations may be helpful.

The balance between carnivorous and non-carnivorous species in aquaculture production is heavily skewed towards the latter. Farming of non-carnivorous species does not rely heavily on fishmeal-based feeds (perhaps 10–15 %, if it is used at all, for some of the more omnivorous species (Tacon, 2000)).

Fishmeal constitutes only 4% of the total oil / meal market demand (Asche and Tveterås, 2000). In 2003, aquaculture used 52.6% of world fishmeal supplies and 86.8% of world fish oil supplies (Chamberlain, Fishmeal Information Network – presentation Aquaculture Today Conference 2006 reference to Tacon). The overall production of fishmeal has changed little over the period which aquaculture of carnivorous fish has developed (1982 to the present day).

Fluctuation in demand and in fish stock sizes caused, for example, by the environmental effects of El Niño, largely determines the changes in market price for fishmeal. Available substitutes (e.g., soya meal) follow similar price trends indicating that soya is a close substitute for fishmeal.

Carnivorous fish culture in the future will not necessarily have to use fishmeal as a protein source. Carnivorous fish can utilize plant proteins in their diets more efficiently than omnivorous fish. Diet formulations for salmonids can, in principle, be made completely fishmeal free without a detrimental effect on growth and with significantly reduced waste outputs (Kaushik *et al*., 1995; Dabrowski *et al.*, 2000). Similar results have now been obtained for cod which required more protein rich diets (see Bell *et al*., 2006).

Improvements in feed conversion efficiency have reduced the amount of fish meal required per unit weight gain of farmed fish (Asche *et al.*, 1999). Protein and energy conversion is generally higher in fish than in warm-blooded terrestrial animals (Steffens, 1989; Åsgård and Austreng, 1995). Whilst the way that Feed Conversion Ratio's (FCR's) are calculated needs to be standardised, it seems likely that even by conservative estimates, that the FCR for salmon could be 1:1 by 2010 (Chamberlain, Fishmeal Information Network – presentation Aquaculture Today Conference 2006).

Should large scale offshore aquaculture of carnivorous fish species occur, and this production be additional to that taking place inshore, the requirement for substitution of fish meal and fish oil will need to occur to a much greater extent. The rate of change will largely reflect the availability of raw materials, cost and consumer attitudes.

4.1.10 Offshore production associated with oil and gas production platforms

Elsewhere in this report we have noted the potential for offshore aquaculture to be developed alongside existing offshore oil and gas production platforms. If fish farms are to be established alongside platforms (within the 500m exclusion zone and beyond) it would be important to take into account both current and historic discharges resulting form these operations which may impact upon the stock.

There is a considerable body of literature related to the environmental impacts of drill cuttings, the toxicity of which varies according to the oil content and the type of drilling mud that was used (see for example: (Neff *et al.*, 1989; Di Toro *et al.*, 1990; Di Toro *et al*., 1992; Det Norske Veritas. 2000; Grant, 2000; http://www.uea.ac.uk/~e130/cuttings.htm - March 2006). Over the past 40 years in the UK and Norwegian sectors of the North Sea, for example, about 1.3 million cubic metres of drill cuttings and associated wastes have built up on the seabed in 102 individual "cuttings piles" with an estimated mass of from 2 to 2.5 million tonnes. The largest pile contains over 66,000m^3 of material and weighs about 100,000 tonnes (http://www.uea.ac.uk/~e130/cuttings.htm - March 2006).

The ecological effects extend for several kilometres from some platforms and can be detected up to 10km from discharge points. These cuttings piles smother the seabed and, when the pile contains oil-based drilling mud, they may remain toxic for many (~20) years. Whilst the level of fish farm detritus arriving per unit area of seabed is likely to be less than in typical inshore situations (see above), the effective degradation and assimilation of this material may not occur at the same rate if these processes are disrupted or prevented by the toxicity of the waste already deposited on the seabed. There has been some concern that disturbance of drill cutting piles might impact on local wild fish stocks. Similar concerns would need to be addressed with respect to fish farm stock.

During oil production, significant quantities of water are produced with the crude oil which, following treatment on the platform, are discharged to the marine environment. This "produced water" contains residues of oilfield chemicals added by the platform operators to the topside processing equipment to aid oil-water separation and mitigate operational problems (Grigson *et al.*, 2000). Field-specific detailed chemical characterisation of produced water from each platform is necessary in predicting the fate and effects of the produced water discharged to the marine environment (Utvik, 1999).

Chemical discharges from offshore platforms are regulated under the Offshore Chemical Regulations 2002 and more information can be found at the DTI website http://www.og.dti.gov.uk/environment/ocr2002.htm. Since 1991 the North Sea countries (UK, Netherlands, Norway and Denmark) have put a lot of effort in the development of a decision support system for the legislation of the use and discharge of offshore exploration, drilling and production chemicals. The heart of this 'harmonised mandatory control system' is the 'chemical hazard assessment and risk management' (CHARM) model. This model enables the ranking of chemicals on the basis of their intrinsic properties, using a realistic worst-case scenario. The CHARM model uses a fixed dilution factor, assuming equal and constant dispersion of chemicals around the platform. In reality, however, chemicals follow a three-dimensional dispersion pattern which will change over time. More recently, models have been developed which give a probabilistic estimation of the ecological risk of produced water, based upon a realistic calculation of the fate of components of produced water after discharge from the platform. Spatial and temporal variation in the concentration of chemicals is summarised in frequency distributions. The ecological risk is calculated for aquatic life, benthic life and the food chain (see Karman and Reerink, 1998).

Typically produced water will contain oil, corrosion inhibitors and demulsifiers (Grigson *et al.*, 2000) together with a wide spectrum of other chemicals (J. Kerr pers comm.). In addition to polycyclic aromatic hydrocarbons and phenols produced waters contain organic acids, naphthalene, phenanthrene, dibenzothiophene, and their C_1-C_3 alkyl homologues, and alkylated phenols. It is the aromatic compounds which are assumed to be the most important contributors to toxicity (Utvik, 1999). Recent *in vitro* evidence has shown that chemicals in produced water can act as estrogen receptor (ER)[24] agonists[25]. Isomeric mixtures of C_1 to C_5 and C_9 alkylphenols contributed to the majority of the ER agonist potency measured in the samples (Thomas *et al*., 2004). In studying the special and temporal toxicity of produced water, Krause (1995) found evidence that field toxicity was directly attributable to the presence of produced water.

In addition to produced water, oil production platforms may occasionally spill relatively small quantities of oil. Whilst the impact of such discharges may be negligible with respect to their wider ecological impact, the fact that they would be occurring in close proximity to a fish farm may have significant consequences.

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[24] A protein within certain cells which can bind to endogenous estrogens, phytoestrogens, or xenoestrogens. Once coupled with its estrogenic molecule, this protein communicates with other molecules and starts a process that ultimately leads to certain genes being switched on or off. The genes regulate many hormone-influenced systems.

[25] An agonist is a substance that binds to a receptor and triggers a response in the cell.

5. OVERVIEW OF THE LEGAL ASPECTS

5.1.1 Introduction

The regulatory and legal regime governing aquaculture in inshore waters is well established in the UK. Comprehensive reviews of aquaculture legislation can be found in Howarth (1990); Van Houtte *et al.,* (1998); Howarth and Leria (1999); Czybulka and Kersandt, 2000; Fernandes *et al.*, (2000); McCoy (2000); Uriarte and Basurco (2001); Buck *et al.*, 2003; Buck *et al.*, 2004) and in various online sources of information on the internet (e.g. http://www.onefish.org – March 2006).

In the UK, The Crown Estate owns the seabed and anyone wishing to build a cage fish farm within territorial waters (out to the 12 nautical mile (nm) limit) must apply for a lease from the District Valuer of the Crown Estate Commissioners. Because cage fish farms are often located in areas frequented by shipping, navigation regulations may have to be complied with. In the UK marine site licences are issued by The Crown Estate Commissioners and applications are forwarded to the relevant groups from an indicative list of stakeholders and individuals through public announcements.

Applications for setting up a fish farm in Scottish waters (out to the 12nm limit) are processed thought the local planning authorities. In addition to obtaining permission from the legal owners of the seabed – the Crown Estate Commissioners and the Department of Transport, coastal cage farms must register with a statutory disease control body (Fisheries Research Services) and obtain a consent to discharge effluents from the Scottish Environmental Protection Agency (SEPA) (Henderson and Davies, 2000; Telfer and Beveridge, 2001). Whilst there are detailed locational guidelines for the authorisation of marine fish farms in Scottish coastal waters (FRS 2002a; Gillibrand *et al.*, 2002), the entire regulatory framework for aquaculture in Scotland is under review. Similar arrangement would be likely to be put in place within the rest of the UK where devolved powers apply. As marine cage aquaculture almost exclusively takes place in Scottish waters, it is here that the regulatory framework is most developed. The practices used in Scotland could easily be applied to marine cage aquaculture development elsewhere within UK territorial waters.

However, new legislation will be required if aquaculture is to take place beyond 12nm (and possibly even beyond 3nm) if the UK is to meet its international and EU obligations. Existing legislation that already applies beyond territorial waters would appear to be deficient. For example, in Scotland, the Water Environment and Water Services (Scotland) Act 2003, defines Coastal Waters as extending to the 3nm limit. As such, SEPA’s powers under Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR) only extend to 3nm. The situation as to who might regulate aquaculture discharges beyond this limit is not clear. It is possible that the Food and Environment Protection Act 1985 (Part II – Deposits in the Sea) (FEPA) might apply but SEPA's normal powers with respect to the regulation of discharges from cage fish farms do not. In this regard, it is interesting to note that the proposed transfer of planning powers in Scotland in relation to fish farms to local authorities include powers for local authorities to give planning consent out to 12nm (D. Sinclair, pers. comm.).

Beyond territorial limits there is no current satisfactory legal basis for giving developers security over a site, nor is there a complete consenting process, and much of the other legislation which regulates and supports aquaculture in territorial waters does not necessarily extend beyond such waters. It is possible that primary legislation will be necessary to build a comprehensive legal framework.

The Marine Consents and Environment Unit (MCEU) is responsible, on behalf of the Secretary of State for Environment, Food & Rural Affairs, for the administration of a range of applications for statutory licences and consents to undertake works in tidal waters and at sea in UK waters and beyond; including marine developments, offshore energy, coast defences, dredging and waste disposal. The Unit also administers certain applications on behalf of the Welsh Assembly Government for which it is the licensing authority in Welsh waters. Similar responsibilities are exercised in respect of works in waters around Scotland and Northern Ireland by the Scottish Executive and the Department of the Environment (NI) respectively.

The Unit provides applicants with a single point of contact; and the ability to make a one-off application for multiple consents (and the option of applying on-line); more integrated administration of applications using a shared consents database and co-ordinated consultation arrangements as well as more holistic scientific assessment of planned works[26].

It would seem logical to assume that the MCEU would be the most appropriate body to co-ordinate the licensing processes that would accord to offshore aquaculture development in England and Wales. The "one stop shop" principle has many potential advantages for would be developers and it is to hoped that this holistic principle is central to regulatory structures proposed under the Marine Bill and strategies elsewhere.

The following sections of this report highlight <u>some</u> of the International, EU and domestic norms, conventions and regulations which may be relevant to the development of offshore aquaculture (beyond the 12nm limit). Our approach is discursive and interested parties are strongly advised to seek legal advice on these matters.

5.1.2 General Definitions

The United Nations Convention on the Law of the Sea (UNCLOS – established in 1982) sets out the rights of a coastal State over its territorial sea and also establishes its rights over the seas beyond these limits. The UK acceded to UNCLOS in 1997. Whilst the UK has full sovereignty over its territorial sea, its rights over the waters beyond the 12nm boundary are more limited.

A coastal State has sovereign rights for the purpose of exploring and exploiting the natural resources of its <u>continental shelf</u>, and the exclusive right to erect structures or installations for these purposes. Natural resources are defined as the resources of the seabed and subsoil and so, for example, include oil and gas. This provides the legal basis in international law for the UK to prospect for and to extract oil and gas from the continental shelf.

Through UNCLOS coastal States such as the UK have the right to establish a 200nm <u>Exclusive Economic Zone</u> (EEZ) around its territory, within which it can exercise sovereign rights in relation to activities such as fisheries, pollution and the production of energy from the water, currents and winds. In addition, the coastal State is given the exclusive right to construct, and to authorise and regulate the construction, operation and use of installations and structures for these purposes. In order to protect these installations and structures, and to ensure safe navigation, a coastal State may establish safety zones around them for a distance of up to 500 metres. In exercising these rights, a coastal State must not interfere with the rights of other States under international law; in particular, the right of freedom of navigation. The UK has not declared an EEZ. However, it has established an Exclusive Fisheries Zone and a Pollution Zone in which it exercises EEZ fisheries rights and pollution control rights respectively.

In line with the development of offshore renewable energy development, it is the UK Government's intention to make an appropriate declaration asserting the UK's sovereign rights in accordance with UNCLOS in relation to the production of energy from the water, currents and winds in a Renewable Energy Production Zone which will extend up to 200nm from the baselines of the territorial sea. Before the UK can exercise EEZ rights conferred by UNCLOS as a body of international law, there has to be legislation at national level which vests such rights with an authority competent to exercise them and defines the limits of the Renewable Energy Production Zone. It would seem likely that a similar zone designation and legislation would be required for

[26] http://www.mceu.gov.uk/MCEU_LOCAL/FEPA/MCEU_role.htm - March 2006

the development of offshore aquaculture operations (see http://www.bwea.com/offshore/further.html - March 2006).

5.1.2.1 International Conventions

The Convention on Biological Diversity (CBD, 1992), UNCLOS (1982) and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention, 1972 and Protocol 1996) deal mainly with the protection of the marine environment and the prevention of pollution. None refer specifically to marine aquaculture. Identification and monitoring of human activities that have an impact on the marine environment are included. Adequate environmental impact assessments are required to be carried out for any new development, followed by specific monitoring programmes.

Through UNCLOS measures to prevent, reduce and control pollution which might be originated by aquaculture are advocated (UNCLOS Art. 194 para. 1, 1982). This convention also requires measures necessary to protect and preserve rare or fragile ecosystems including the habitat of depleted, threatened or endangered species (UNCLOS Art. 194 para 5, 1982). The CBD deals with impact assessments and avoiding or minimising adverse effects in general (Para. 14; CBD, 1992). Within the London Convention all practicable steps are to be taken to prevent pollution of the sea by the dumping of waste and other matter that is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea (See Buck *et al.*, 2003; Buck *et al.*, 2004).

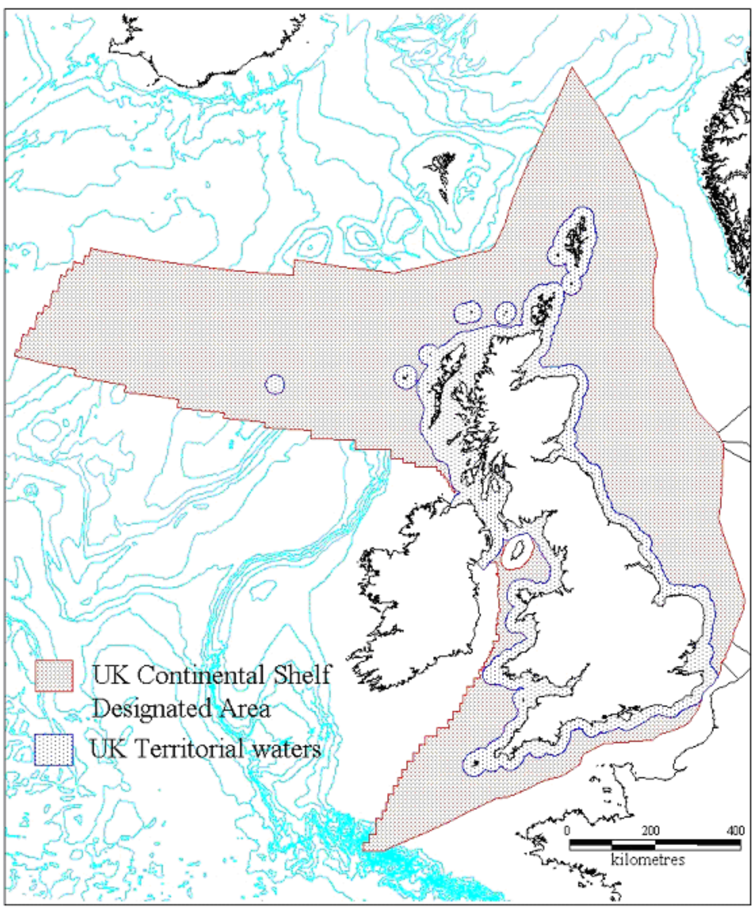

Figure 20 Likely maximum extent of UK offshore area. Based on UK Continental Shelf designations, and including UK limit of territorial waters (12nm). (Note that the area is not

coincident with the 200nm fisheries limit.) The total extent of UK waters (UKCS designated area and territorial waters) is approximately 867,400km^2, of which 161,200km^2 is territorial waters (including around Rockall) and the offshore area 706,200 km^2. These figures exclude the territorial waters of the Isle of Man and the Channel Isles (After - http://www.jncc.gov.uk/page-1478 - March 2006). World Vector Shoreline copyright US Defense Mapping Agency, Bathymetry copyright GEBCO Digital Atlas, British Oceanographic Data Centre on behalf of IOC and IHO 1994 & 1997. UK Continental Shelf designations courtesy Department of Trade and Industry via DEAL website www.ukdeal.co.uk

Under Agenda 21[27] (http://www.un.org/esa/sustdev/documents/agenda21 - March 2006), the impacts of aquaculture are discussed in the “Sustainable use and conservation of marine living resources under national jurisdiction” (Section II, Chapter 17, program area D). Coastal states are requested to conduct analysis of the potential of aquaculture and to implement mechanisms to develop mariculture and aquaculture within areas under national jurisdiction where assessments show that marine living resources are potentially available (17.79c, 17.83). Explicit in the language of Agenda 21 is the need for developed countries to ensure that states should provide for the transfer of environmentally sound aquaculture and mariculture technologies (17.92a) (See Buck *et al.*, 2003; Buck *et al.*, 2004).

The United Kingdom is a signatory to the "UN/ECE Convention on access to information, public participation in decision-making and access to justice in environmental matters" known as the Aarhus convention. Article 1 of the Aarhus Convention states that: "In order to contribute to the protection of the right of every person of present and future generations to live in an environment adequate to his or her health and well-being, each Party shall guarantee the rights of access to information, public participation in decision-making, and access to justice". In May 2003 in response to the Aarhus convention the EC adopted Directive 2003/35/EC –The Public Participation Directive. The Directive intends to implement the provisions of the Aarhus Convention on public participation in decision making and access to justice in environmental matters by amending Environmental Impact Assessment (EIA) and Pollution Prevention and Control (PPC) Regulations.

5.1.2.2 Regional Conventions

The Oslo-Paris Convention of the Protection of the Marine Environment of the North-East Atlantic (OSPAR) identifies aquaculture as the technology to raise fish, molluscs and crustaceans (Czybulka and Kersandt, 2000). In addition to these convention articles, the Quality Status Report of OSPAR (QSR, 2000) records the actual condition of the impacts of human activities through aquaculture on the environment in terms of the release of metabolic wastes, antifoulants (copper), antibiotics, vaccines and parasites into the water column.

The International Conference on the Protection of the North Sea (NCS) does not take any position on regulation of aquaculture, but fosters the political impetus for the intensification of the environmental protection work within relevant international conventions, and ensures more efficient implementation schemes for the existing international rules related to the marine environment in all North Sea jurisdictions.

The Convention for the Conservation of Salmon in the North Atlantic Ocean was established in 1982 (http://www.nasco.org.uk – March 2006). The North Atlantic Salmon Conservation Organization (NASCO) established the International Atlantic Salmon Accord (CNL(98)73) in 1998. The Accord is a comprehensive plan to combat the threats to salmon at all life stages, in

[27] Agenda 21 is a comprehensive plan of action to be taken globally, nationally and locally by organizations of the United Nations System, Governments, and Major Groups in every area in which human impacts on the environment – see also: Rio Declaration on Environment and Development; Commission on Sustainable Development; United Nations General Assembly meeting in special session.

both its freshwater and marine habitats. Created and launched at NASCO at Edinburgh, Scotland in 1998 by the Atlantic Salmon Federation of North America and the Atlantic Salmon Trust of the United Kingdom, the accord makes specific reference to salmon aquaculture.

The Williamsburg Resolution, to Minimise Impacts from Aquaculture, Introductions and Transfers, and Transgenics on Wild Salmon Stocks was adopted in 2003 – amended 2004 (CNL(04)54).

This resolution aims to minimise escapes of farmed salmon to a level that is a close as practicable to zero through the development and implementation of action plans as envisaged under the Guidelines on Containment of Farm Salmon (CNL(01)53);
• Minimise impacts of ranched salmon by utilizing local stocks and developing and applying appropriate release and harvest strategies;
• Minimise the adverse genetic and other biological interactions from salmon enhancement activities, including introductions and transfers;
• Minimise the risk of transmission to wild salmon stocks of diseases and parasites from all aquaculture activities and from introductions and transfers.

5.1.2.3 EU Directives

There are a plethora of EU Directives which pertain to aquaculture and an exhaustive analysis is beyond the scope of this report. Whilst these Directives are enacted through domestic legislation, until recently, the assumption has been that this applied only out to the limits of UK Territorial waters. Within the EU there is currently a debate, whether directives regarding to the protection of birds (Council Directive 1979/409/EC) and habitats (Council Directive 92/43/EC), should apply beyond the 12nm zone (Ducrotoy, 1999). The notion that the provisions of the Habitats Directive did not extend beyond the 12nm limit of the territorial sea to the UK Continental Shelf was successfully challenged in the High Court in November 1999 (R -v- Secretary of State for Trade and Industry *ex parte* Greenpeace Limited [2000] 2 CMLR 94). Consequently, the proposed Offshore Marine Conservation (Natural Habitats &c.) Regulations 2003 set out the proposed regulations to apply the Habitats and Birds Directives to the UK Continental Shelf and waters beyond 12nm from the baselines over which the UK exercises sovereignty. The Regulations will afford protection to species listed by the Directives (primarily cetaceans, turtles, certain fish and birds), as well as requiring Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) to be identified and protected. All protected sites currently lie within territorial waters and are attached to the coast. A further stage of Natura 2000 site selection has now commenced to select sites beyond coastal waters and fully detached from the coast. The Joint Nature Conservation Committee (JNCC), in partnership with the country conservation agencies, is leading on the selection of sites beyond territorial waters. The identification and proposal of SACs which are fully detached from the coast but lie in territorial waters remains with the relevant country conservation agency.

This judgement presumably provides a precedent for other Directives relevant to conduct out to the full extent of the EEZ's of EU countries. In the absence of national legislation, it seems likely that EU and International law would be the principal framework within which offshore aquaculture would develop. However, as with other activities which take place beyond the 12nm limit and out to the 200nm EEZ, it would seem desirable and inevitable that a similar national legal and regulatory framework should be established for offshore aquaculture operations as applies inshore – particularly, if the UK is to remain compliant with its other international obligations as outlined above.

The European Strategic Environmental Assessment Directive (Directive 2001/42/EC) was not incorporated into UK law until 2004. Strategic Environmental Assessment (SEA) is the process of appraisal through which environmental protection and sustainable development may be considered, and factored into national and local decisions regarding Government (and other) plans and programmes – such as oil and gas licensing rounds. The Department of Trade and Industry (DTI), as the principal regulator of the offshore oil and gas industry and it would seem likely that they would, in collaboration with the Marine Consents and Environment Unit (see above) adopt this role with respect to the licensing of offshore aquaculture installations.

The structure and implementation of the EU Water Framework Directive (WFD) (Directive 2000/60/EC), which is presently under development by all EU countries, will be of particular relevance. Through the WFD, the EU is establishing a framework for the protection of all waters (including inland surface waters, transitional waters, coastal/offshore waters, and groundwater), which includes the following objectives to:

* prevent further deterioration of water resources,
* promote sustainable use of water based on long-term protection of water resources.

Whilst the WFD appears to be designed to cover coastal waters out to one or two miles (3nm in Scotland) from the coast, it seems clear that future legislation (see EU Marine Strategy) may use the WFD as a template for regulating offshore waters.

The EU is currently revising primary legislation relevant to fish and shellfish health. The new Directive will repeal existing primary legislation (Council Directives 91/67/EEC, 93/53/EEC and 95/70/EC). A key objective of the revised legislation is to simplify and modernise existing legislation and procedures on aquatic animal health. The new Directive brings the rules for placing aquaculture animals and products on the market in line with the standards of the World Organisation for Animal Health (OIE). The rules must also be updated to bring EU rules in line with international agreements and standards (like the World Trade Organization Agreement on the Application of Sanitary and Phytosanitary Measures - the SPS agreement). It aims to both improve intra-Community trade and make it easier for third countries to trade with the EU by providing harmonised, clear cut rules on aquaculture. Defra has started the process of reviewing and updating the Fish Health Regulations 1997 (No. 1881) to reflect changes at EU level. At present, it is not clear if new EU Directive or revised UK legislation will apply beyond territorial limits.

The European Commission Directive 2004/35/EC (2004) which defines environmental liability with regard to the prevention and remedying of environmental damage is based on the underlying premise of the “polluter pays principle” which in theory could apply to certain aspects of aquaculture production. Whilst this could apply within territorial limits, as with other aquaculture relevant EU Directives, there is reason to suspect that they may also apply out to the limits of the EEZ.

5.1.2.4 Codes of Conduct

A number of international and industry led codes of conduct apply to aquaculture production and it seems somewhat ironic that offshore aquaculture could effectively be more stringently “regulated” beyond the 12nm limit by adherence to voluntary codes than through the existing legal framework. In addition, much aquaculture production is undertaken with strict reference to quality standards enforced by its main customers – the multiple retailers.

At an international level, the Food and Agriculture Organisation (FAO) refers specifically to aquaculture development in its Code of Conduct for Responsible Fisheries (1995) (Art. 9) and under the Technical Guidelines for Responsible Fisheries (1997) (Art. 5).

The International Council for the Exploration of the Sea (ICES) – Code of Practice on the introductions and transfer of marine organisms (2003) follows the precautionary approach adopted from the FAO principles (FAO, 1995), with the goal of reducing the spread of exotic species, including genetically modified organisms. There are elements of this code which could apply to offshore aquaculture.

In addition, OSPAR makes recommendations for the reduction of inputs of potentially Toxic Chemicals from Aquaculture Use (PARCOM Recommendation 94/6 on Best Environmental

Practice (BEP)) and invites Contracting Parties to draw up BEP codes and action programmes for the reduction of such inputs from aquaculture. It lists constituent elements for inclusion in action programmes and BEP codes.

5.1.3 Future Legislation

5.1.3.1 European Marine Strategy

The Marine Strategy is aimed at protecting Europe's seas and oceans and ensuring that human activities in these seas and oceans are carried out in a sustainable manner so that "we and future generations can enjoy and benefit from biologically diverse and dynamic oceans and seas that are safe, clean, healthy and productive". While there are measures to control and reduce pressures and threats on the marine environment, there is no overall, EU level, integrated policy for protection of the marine environment. Therefore, an integrated approach taking into account all the pressures on the marine environment needs to be developed, setting clear sustainable objectives and targets to be met through a set of cost-effective measures.

There will be two main elements to the Marine Strategy; a Communication and a Framework Directive. The Communication would briefly describe the state of the marine environment, the pressures acting on the marine environment and the need for action. The objective of the new Marine Framework Directive would be to protect, conserve and improve the quality of the marine environment in marine waters, through the achievement of good environmental status in European seas within a defined time period. The Directive will define/establish ecosystem-based marine regions as the implementation unit. These will be defined on the basis of their hydrological, oceanographic and bio-geographic features. An Implementation Plan, defined as an integrated framework for the adaptive management of human activities impacting on the marine region, would be prepared for each marine region.

It would seem logical that the Marine Directive would be applied to those marine areas seaward of the boundary of the area currently being covered by the WFD (more than 1 or 2 miles offshore). However, there is currently some lack of clarity in this area, and it may be that the Marine Directive would apply to coastal and transitional waters as well as to offshore waters and therefore overlap with the WFD in these areas. If aquaculture is to take place in the offshore areas outwith the intended remit of the WFD, it is important that this is taken into account in the development of the Marine Directive.

5.1.3.2 UK Marine Bill

The Government's vision for the marine environment is for clean healthy, safe, productive and biologically diverse oceans and seas. To help deliver this vision Defra is preparing a Marine Bill with the aim of putting in place a better system for delivering sustainable development of the marine and coastal environment. The Bill will address both the use and protection of marine resources. Introduction to Parliament will be dependent on the availability of Parliamentary time, but it is expect that the likely date will be sometime during 2007. As precursor to the development of the Bill, the consultation process has sought comment on:

- How to take forward Marine Nature Conservation proposals: the review of Marine Nature Conservation published in 2004 recommended the government seek new legislation for the delivery of an effective network of Marine Protected Areas (MPAs).

- The reform of marine licensing regimes

- A strategic system of Marine Spatial Planning (MSP): this could provide a framework for managing activities in the marine area.

- A potential new Marine Management Organisation (MMO).

The forgoing sections related to overarching International and EU legislation and its relationship to national legislation highlight the need for clarification of responsibility for the regulation of aquaculture beyond 3nm and 12nm territorial limits. As the use of the coastal zone intensifies, and the desire to exploit waters beyond territorial limits increases, it would be helpful if the Marine Bill could explicitly address the need to establish a clear framework.

Whilst the Marine Bill would cover activities relevant to England and Wales, Scotland is also preparing a Marine Strategy. The importance of these legislative developments should not be underestimated, as they clearly reflect a move towards the "holistic" principles of ICZM and the all pervading theme of sustainability. If aquaculture is to expand beyond the limits of the coastal zone, it is important that the option to do so is secured as part of this fundamental legislative revision.

5.1.4 Other considerations relevant to offshore fish farm development

5.1.4.1 Stock loss and ownership

The biological issues related to escapes have been dealt with in other areas of this report. There are, however, some legal considerations that may need to be addressed if measures to mitigate the effects of escapes are to be used offshore. Under the NASCO Convention (1982, Art. 2), it is illegal to fish for salmon beyond the 12nm limit. In principle, it would therefore not be possible to attempt to recapture escaped salmon stock. For other species of fish where, for example, there was a local/regional prohibition on fishing (as part of stock conservation measures), the same principle might also apply. In order to conduct aquaculture offshore, it would be important to ensure that legal ownership of the captive stock was defined as part of the operating licence. For most offshore installations, a 500m exclusion zone is enforced which can exclude fishing for example and thus afford some protection of stock. Outwith this exclusion zone, one must assume that the stock could legitimately be captured by anyone, subject to the provisions mentioned above.

5.1.4.2 Navigation

It is essential to ensure that marine fish farm development does not constitute a hazard to navigation. In Scottish Waters for example, fish farm related navigational consent is granted by the Scottish Executive Enterprise, Transport and Lifelong Learning Department (SEETLLD), under the provisions of the Coastal Protection Act, usually following the grant of the works licence or seabed lease (because the process of dealing with these other licences includes consideration of navigational issues). It is assumed that an offshore fish farm would be subject to the same navigation regulations as would apply to any fixed offshore installation. The appropriate risk assessment methodology would need to be applied and permissions granted by the Department of Trade and Industry (DTI). The use of single point moorings and submersible fish cages and infrastructure could potentially increase the risk of collision.

5.1.4.3 Decommissioning of offshore installations (which would include fish farms)

Under UNCLOS (Art. 60) any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent International organization, and that such removal shall also have due regard to fishing, protection of the marine environment and the rights and duties of other States. As the competent International organisation, The International Maritime Organisation (IMO – Resolution A.672(16) 1989) provides guidelines and standards for the removal of offshore installations and structures on the continental shelf and in the exclusive economic zone.

5.1.4.4 Monitoring and enforcement

Aquaculture in UK coastal waters is highly regulated. The contingent cost of monitoring and enforcement is high and much of this cost is borne by the industry. The logistics and associated costs of ensuring similar levels of regulation offshore will be considerably higher. These factors will need to be considered as part of the overall assessment of economic viability.

6. OVERVIEW OF TECHNICAL CONSIDERATION AND CURRENTLY AVAILABLE AND PLANNED OFFSHORE PRODUCTION SYSTEMS WHICH MAY BE SUITABLE FOR USE IN UK WATERS

6.1.1 Technical Considerations

6.1.1.1 Offshore site conditions relevant to cage design and operation.

Scott and Muir (2000), Muir and Basurco (2000), Buck, (2002), Beveridge (2004), Ryan (2004), and Ágústsson (2004), provide comprehensive reviews of most of the cage structures that either purport to be capable for use, or are used in exposed locations, some of which could potentially be described as “offshore” cages. For the purposes of this report, the terms “cage”, “net pen” and “enclosure” will be largely interchangeable and refer to the containment facility for the captive stock of fish.

Turner (2000) and Ágústsson (2004) provide a list of key terms and definitions pertinent to the design and location of fish cages or enclosures. The parameters defined are relevant to physical and engineering considerations as well as some fundamental biological and operational factors which could affect the viability of an offshore fish farm (see Tables 1 and 2).

Table 5 After Turner 2000

Parameter	Definition
Significant wave height	*Hs* or *H⅓*: Defined as the average of the highest one third of the waves in a given wave height measurement data set (wave spectrum). Wave data is usually published as significant wave heights and corresponding wave periods.
Orbital wave particle motions	Waves propagate with a certain speed in the water but the individual water particles do not. They move in particle orbits. Close to the surface their orbits are elliptical but with increased depth these orbits become circular in shape
Wave hindcasting	An important process for determining wave climate from wind statistics, given some knowledge of wind systems and fetch lengths.
Windspeed return period:	Defined as the probability of a certain windspeed event in any given year. Usually it is used in terms of the maximum windspeed for example 20, 50 or 100 years. A related term is wave height return period. A structure is often designed in such a way that it can withstand forces due to a wave height with certain return period (probability of occurrence in any given year). See design wave.
Design wave	Defined as the highest wave that a structure is designed to withstand. Its return period is estimated and the structures lifetime calculated with respect to this estimate. The biggest wave likely to occur does not necessarily produce the most critical loading on offshore floating structures (near to the surface).

6.1.1.2 General climatic considerations

Extreme weather conditions are key concerns in assessing the risks associated with offshore aquaculture, particularly in light of predicted climate change and the potential for more frequent and intense storm activity in UK waters (Hulme, *et al.*, 2002). Any offshore development will need to carefully consider the implications of these predictions with respect to cage life. Structural components will inevitably be more stressed more often, reducing fatigue life, increasing maintenance costs and the chances of structural failures. Barker (1990) suggested that extreme values of environmental factors which are not exceeded once in every 100 years should be used for locating fish farms. However, in waters where the environmental data is well established, e.g. the European continental shelf, a 50-year return period may be acceptable. Nayak *et al.,* (1990) suggested that only 5-10 years wave data is necessary for reasonable prediction of a maximum design wave. Perez *et al.*, (2003) assume that a return period which covers the lifetime of the structure (15-20 years) is satisfactory for siting an offshore cage system. However, the capital investment involved in many proposed offshore ventures would suggest that a conservative approach to return periods should be used to mitigate as much risk as possible.

6.1.2 Wave Climate

From a technical and engineering perspective the prevailing wave climate (wave action) in the offshore is the prime consideration and it is important to have a basic understanding of the underlying principles to analyse the various technical approaches that have been proposed or adopted to meet the challenge of cultivating fish offshore. A proportion of the wave energy absorbed by a cage will be translated into kinetic and potential energy causing the cage to move, the residual forces being either dissipated within the structure or transmitted to adjoining cages, moorings and the water (Beveridge, 2004). The impact on the cage structure and nets causes structural load, wear, fatigue and ultimately failure. For the captive stock, excessive wave action (the motion of the water relative to the cage and the stock) can cause physiological problems (osmotic stress) due to loss of scales from the fish, reduced growth performance, physical damage and mortalities (Turner, 1991).

6.1.2.1 Wave Height

Waves differ in origin, form and velocity. Those that are of paramount importance for cage aquaculture are generated by the wind. Wave height increases with wind velocity and wave energy increases proportionally with the square of wave height (see Figure 21). Water movement produced by waves is largely a surface phenomenon. As a wave moves across the sea (in the open ocean), it can be seen that particles (within the wave) tend to rotate in circular orbits. At the surface, the diameter of the orbit is equal to H, the wave height. However, the orbit of particles decreases exponentially with depth and is expressed as follows:

Equation 1. $D_z = H^{(2z/L)}$

D = diameter of the orbit; z = depth; L = wavelength (Pond and Pickard, 1983).

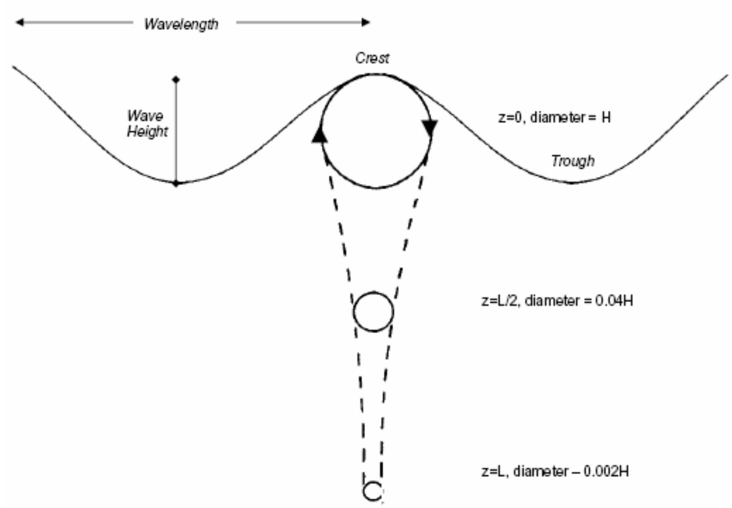

Figure 21 Rotational properties of water particles in a wave (Modified after Pond and Pickard 1983)

It is important to be able to predict the highest waves and most damaging wave periods and frequencies that are likely to occur at the offshore site. In order to assess the likely wave characteristics at a site, information on the long term frequency and direction of surface wind speeds is needed (usually derived from hindcasting). These data are widely available for UK waters and are becoming increasingly detailed, as a result of satellite altimeter derived data, (see for example: http://www.noc.soton.ac.uk/JRD/SAT/Waves/GWC_pt1.htm - March 2006; http://www.globalwavestatisticsonline.com - March 2006 and the Atlas of the UK Marine Renewable Energy Resources, Anon 2004).

Both likely highest waves over a given period (design wave or return wave) and prevailing or average wave heights are significant measures in assessing the cage system structure. The former may cause instant total failure, while the latter will promote gradual failure through structural fatigue. For the design of coastal and offshore structures it is important to predict the combined effect of the extreme wave height and associated wave period (Liu and Wang, 1986). The significant wave height (Hs) is the mean height of the highest 33% of waves and is around 40-60% higher than the overall mean wave height. The maximum wave height at a site may be 1.8 - 2 times the significant wave height (Dean, 1990; Turner, 2000).

Perez *et al*., (2003), have developed a methodology to assist in offshore site selection (see also Scott, 2003; Smith, 2005). Perez *et al.*, focus solely on wave height estimations as this is a more general and straightforward indicator for siting cages. The use of wave periods, although an important variable, is more dependent on the cage design, mooring structure, cage orientation, etc. (Whittaker *et al*., 1990).

6.1.2.2 Wavelength and period

Wavelength and period, which are not normally considered for site selection, are important wave effect features when designing offshore floating structures. Whittaker *et al*. (1990) concluded that longer period waves produce the highest mooring loads and the largest drift movements of cages, whilst the shorter period waves produce the largest angular displacement of the joints. Cage loads associated with longer ocean swells (greater wave length) have been found to be relatively small, whilst maximum forces are associated with shorter and more frequent waves generated by local storms (Pond and Pickard, 1983; Isaacson *et al*., 1993). The range of dynamic force on mooring lines decreases significantly with increasing wavelengths. As the wavelength increases, the depth to which the wave loading penetrates also increases, affecting the distribution of forces on structures at different depths (Isaacson *et al*., 1993). Perez *et al*., (2003) suggest that further improvement of their model could include the combined use of the wave heights and wave periods. Coastal swell typically has wave lengths of 7-15 seconds (Turner, 2000). Some Scottish sites exposed to the open Atlantic Ocean experience heavy swell, which has caused descaling of fish and consequent high mortalities through excessive motion of the cage bag (Beveridge, 2004). Perez *et al*., (2003) acknowledge that for non-oceanic locations, the inclusion of current data together with bathymetry and seabed slope would give improved characterisation of marine conditions.

6.1.2.3 Wave forces

Vertical dynamic forces imposed by waves tend to be the most important as these exert bending and torsional forces. Bending forces are at a maximum at wavelengths similar to the dimension of the cage hence inshore sites may be as vulnerable to such forces as offshore sites. Cyclical stresses imposed by the periodicity of the waves may cause fatigue in cage members, which may be of greater significance than occasional very large waves. In this respect, inshore sites with short fetches and small wave periods may be worse than offshore sites (Beveridge, 2004).

Modelling the dynamics of the forces acting upon cage structures is a complex and evolving area of science and engineering, but some basic analysis is possible that can help to inform the process of assessing the types of cage structures that are likely to be required to meet both the physical and biological demands of operating in offshore conditions.

There are various formulae for estimating the maximum horizontal force from waves on the center-point of objects of large dimensions and various geometry (see Silvester, 1974). According to Ágústsson (2004) the most commonly applied estimation is Morison's Equation (see Equation 2) which is generally applied to slender offshore structures (Hughes and Burcharth, 2004).

Equation 2. $$F = \underbrace{\left(m_{11} + \rho\forall\right)\mu}_{Inertial\ \ force} + \underbrace{\tfrac{1}{2}\rho l^2 C_D \mu \mid \mu \mid}_{Drag-force}$$

F = horizontal wave force
ρ = specific mass of water
l = object length
m_{11} = effective mass of fluid that surrounds the object
$\forall$ = displaced volume of the fluid
μ = fluid acceleration
C_D = drag coefficient
$\mu \mid \mu \mid$ = squared fluid velocity

The first term of Morison's Equation, the inertial force, is the force required to hold the object in place subject to a constant free stream acceleration. The second term, the drag force, is the force required to hold the object in place subject to a stream of certain velocity.

Fredriksson *et al*., (2003a and 2003b) suggest a use of a modified version of the Morison's Equation to account for relative motion between the structural elements and the surrounding fluids, and coefficients of drag and added mass (inertia) respectively. Lader *et al*., (2001) suggest drag and lift coefficients (C_D and C_L) for modelling of a simple net exposed to waves and currents in three dimensions.

The influence of drag and inertia forces will be highly dependant on the size and shape of the cage system and wave characteristics. Spherical cages will encounter oscillations. Netting deflection will vary depending upon the type of cage. For most submersible rigid cages or tension anchor of tension leg structures where the net is highly tensioned this factor may not be significant. Similarly, the distribution of force over the structures surface will vary and the effect of the distribution of the fish in the cage may also need to be taken into account.

6.1.3 Current characteristics

Currents have relatively simple characteristics compared to waves. They may be considered uniform with depth except close to surface and to the seabed (Silvester, 1974), and divide into two main categories:

- Currents with long fetch resulting from deep-sea flow – as found in the open ocean. Low velocities.
- Currents due to tides, for example in bays and channels. High velocities.

6.1.3.1 Current forces

Currents can have significant influence on the loads experienced by an object in the ocean, for example by increasing the amplitudes of forces from wave action (Skourup *et al.*, 2000), and by affecting wave lengths and direction of wave propagation (Silvester, 1974). Currents effects may be included in the overall wave loading by superposition[28] (Sarpkaya and Isaacson, 1981).

[28] The principle of superposition may be applied to waves whenever two (or more) waves travelling through the same medium at the same time. The waves pass through each other without being disturbed. The net displacement of the medium at any point in space or time is simply the sum of the individual wave displacements.

Whilst wave forces may be dominant factors in design nearer to the surface, strong and persistent currents at depth may also be critical as they place the cage, moorings and stock under constant load imposed by drag forces. These forces depend on the geometry and size of the objects exposed to the current. According to Ágústsson (2004), drag forces quadruple relative to increasing current speed such that an increase of current speed from 0.2 - 0.8ms^{-1} (a fourfold increase) will result in a sixteen times greater drag force. Farmocean International AB, producers of a well known "offshore" fish cage design (see below), do not recommend fish farming in currents above 1.3ms^{-1} (http://www.farmocean.se, October 2003 – in Ágústsson, 2004).

6.1.3.2 Cage currents

In addition to understanding the effects of current on the cage, it is also of profound biological importance, with respect to the welfare and performance of the captive fish stock to be able to predict the currents that will occur within the cage. Whilst current velocity within the cage (relative the external current) will be affected by the type and gauge of the net material, the degree of fouling and to a certain extent the movement of the fish themselves, a reduction factor is provided by Lee and Pei-Wen, (2000) for the current velocity flowing through a net, indicating that the current velocity is reduced to about 74% of its original value when the water flows through the net. This means that cages facing a current with velocity 1ms^{-1} could experience currents of about 0.7-0.8ms^{-1} inside them, which is considerably higher than recommended for fish species like Atlantic cod (Ágústsson, 2004).

6.1.4 Other Forces to be Considered

Few authors consider the effect of pressure when discussing the forces acting upon cage structures and depth limitations on submersible cages are rarely quoted. Pressure increases with depth and to a certain extent wave characteristics (Sarpkaya, and Isaacson, 1981). It is generally assumed that most designs are robust enough to withstand submersion to considerable depth before pressure becomes a defining factor in force calculations (Ágústsson, 2004) and that this assumption holds for a depth of at least 15m (Celikkol *et al.*, 2004). However, many cage designs may not be capable of submergence to the depths necessary to avoid extreme wave conditions. Ágústsson (2004) for example, quotes operational depths of 30 to 50m (depending upon current) to achieve similar "force" conditions as would apply in relatively quiescent inshore sites (see Figure 21). Whilst the forces imposed on submerged structures are reduced with depth, it is likely that most farms will require surface infrastructure of some kind which will need to withstand significant and extreme wave forces. Since many of the so called "open ocean" fish cages are not designed to submerge to depths of a few tens of meters, they would still face heavy loads in extreme wave conditions (Ágústsson, 2004).

The wave parameters used by Ágústsson (2004) are for open ocean conditions experienced off the south coast of Iceland. The minimum parameters used to describe offshore conditions (Table 2) suggest significant wave heights (Hs) of at least 5m. If we assume the maximum wave height of twice Hs (see above) which would be 10m (Dean, 1990), and similar wave period, current speed and depth parameters which would not be unreasonable for large areas of UK offshore waters the minimum submergence depth required to achieve a "sheltered site" equivalent would be at least 20m. These parameter estimates would certainly be an underestimate of conditions in some areas where offshore oil and gas productions takes place in the North Sea, suggesting that depths of in excess of 30m submergence would be required to achieve "sheltered site" conditions. By way of example, Ninian Central Platform in Block 3-3 of the North Sea lies about 100 miles east of Shetland in a water depth of 133m. The maximum wave height is about 18m with current speeds ranging from about 0.8ms^{-1} at the surface to 0.5ms^{-1}, 10m above the seabed (R. Thompson, pers. comm.).

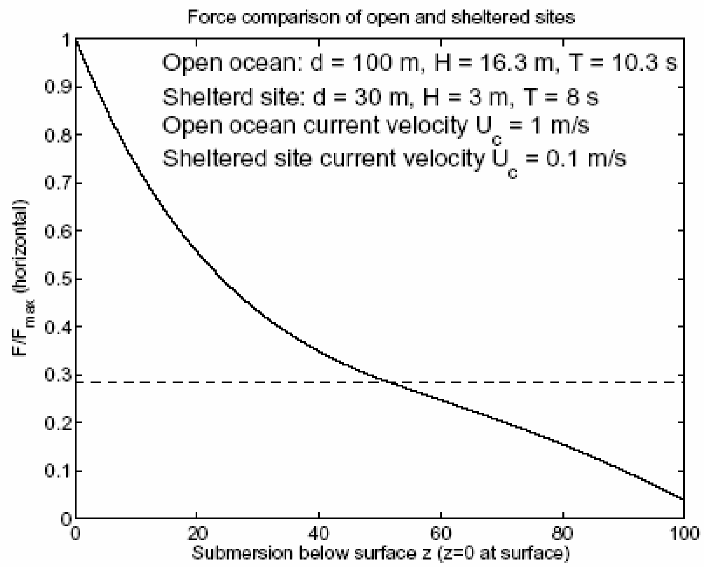

Figure 22. A comparison of an extreme open ocean conditions of waves and currents and sheltered site conditions of low waves and weak currents using Equation 2 (dotted line indicates that a submersion in the open ocean of about 31m will result in loads comparable with those at surface at a sheltered site (F/Fmax (horizontal) = maximum horizontal force, d=depth in metres, H = maximum wave height in metres and corresponding wave period, T in seconds, U_c = current velocity in meters per second) (after Ágústsson, 2004).

There is obviously a strong seasonal component to the both wave climate and temperature. Careful forecasting could permit cages to be raised and lowered to take advantage of optimal conditions and minimising the impact of adverse weather. However, the impact of this practice on the stock will need to be considered, together with the changes in husbandry and logistics that will need to apply under what may be significantly different operational conditions.

6.1.5 Cage and Enclosure Designs

Scott and Muir (2000), Ryan (2004) and Ágústsson (2004) provide the most recent, practical overviews of “offshore” cage systems. The salient points from these publications will be summarised in this report together with information on designs which have been advanced subsequent to these publications. It is important to note that many of the designs are conceptual, some may have been tested in the field, but no cage systems capable of operating in UK offshore (as opposed to exposed) conditions (see Table 1 and Table 2, Class 4 or above) have ever been deployed commercially.

Cages, enclosures or any other form of containment must, in the context of offshore aquaculture, be regarded as part of an integrated package of systems and measures which either exist and could be adapted for use offshore or would require novel innovation. As will be discussed, many aspects of fish husbandry, farm operation and maintenance will need to be developed in parallel with containment facilities if offshore aquaculture is to succeed. Development of much of this “ancillary” equipment and associated changes in working practices appears to have lagged behind cage development. Indeed, the failure of some of the systems tested can often be attributed to a lack of planning and a focus on the “cage” rather than adopting an integrated and systematic approach to production and marketing. (see Muir *et al.*, 1996; Scott and Muir 2000; Ryan, 2004).

Many “offshore” cage designs have been developed by dedicated research teams, existing cage manufacturers, net manufacturers, naval architects, ship builders, and offshore oil hose manufacturers. However, Scott and Muir (2000) contend that few appear to have been developed with reference to experienced fish farmers! As a result, the cage types on offer are generally expensive and often deficient in terms of holding and managing fish.

Offshore conditions will dictate that many routine fish farming activities will need to be conducted remotely and with less frequent human interaction. The experience of the offshore oil and gas sector could provide some valuable technical solutions. Recent advances in communications and telemetry, greatly enhances the prospect of bring together the suite of developments necessary to establish fish farms in truly offshore conditions. However, monitoring and managing fish remotely under offshore conditions has not been tested on any significant scale. There is often considerable pressure to deploy conceptual designs to gather “real field data”. From both a commercial and scientific perspective this generally results in expensive failures. Logically, given the number of significant variables highlighted in this report for which there is little or no data to support a particular mode of action, a reductionist view of the need for systematic research and development is valid.

Loverich *et al.*, (1996) and Scott and Muir (2000) propose various classifications of cage structure. To aid comparison in this report, designs have been brigaded on the basis of the way the net is supported. Available information has been summarised, but it is important to recognise that few published reports are available on the performance of the majority of the cage structures. Much of this information is either not known or is unavailable. The cages highlighted are not a complete list of the offshore designs that have been proposed or developed, but they are considered representative of the principal system designs and concepts.

A common way of expressing cage cost is to quote the cost per unit volume. Whilst this figure is a rough comparator between cages costs, it can be highly misleading. Some cage systems include additional infrastructure for feed storage and personnel for example, whilst some of the simple flexible designs have separate facilities that are not usually included in the “nominal” per unit volume cost. Bugrova (1996) studied the economic feasibility of three different cage systems, including offshore cages for sea bream production in the Mediterranean and suggested that capital cost is 43% higher for semi-submerged than for floating cages, however this is compensated by lower labour costs, lower feed costs, better survival rate and higher fish quality. Burgova concluded that in ‘real terms’ the unit production costs for floating systems are 3% higher than those for semi-submerged ones. No other detailed economic comparisons are available. It is likely that the only way to develop a meaningful economic evaluation is on a site-by-site and cage-by-cage basis. Much or this information could, however be derived through detailed economic and financial modelling.

6.1.6 Comparison of Cages and Enclosures

6.1.6.1 Surface (and submersible) gravity cages

Description:
Square or circular buoyancy collar system with a weighted net enclosure suspended beneath.

Examples:
Surface (and submersible) gravity cages – Kames (Scotland), Bridegstone (Japan), Dunlop (Ireland), Marine Construction (Norway), PolarCirkel (Norway) (see Figures 23 and 24).

Construction:
Square or circular floatation collars made of wood, steel, plastic and or rubber, with a net suspended beneath the collar and weighted to maintain the enclosure volume. In the flexible collar types such as Bridgestone, Dunlop and PolarCirkel, the cage collar maintains the shape of

the net, but is not designed for working operations which are all carried out from rafts or support vessels.

Volume(s):
Bridgestone – largest currently available >40,000m^3. Dunlop and PolarCirkel are similar.

Cost m^{-3}*:*
Due to the large holding volumes possible, capital costs per m^3 can be very low, e.g., 16 m octagonal cage of 20 m depth (25,000 m^3) = £5-6 m^{-3}. Costs of smaller systems are relatively high due to the limited volumes enclosed = £25 m^{-3}. This cost does not include the need for vessels to support this type of cage operation.

Status:
Used extensively in the near shore low energy environments (Class 1, 2 and slightly modified for Class 3 sites). The Bridgestone cage, originally designed for holding tuna, is in widespread use around the world with over 300 units in operation. Very large cage volumes are possible – the largest has a circumference of 160 m and depth of over 20 m. Bridgestone cages are used in the Mediterranean for tuna, sea bass and sea bream and in Ireland and the Faroes for salmon. Surface gravity cages are generally considered as unsuitable for offshore conditions (Fredriksson et al., 2002, 2003), but the recent and successful use of massive flexible collar gravity cage systems in the development of tuna on-growing in open ocean operations suggests that refinement of such systems may be warranted. Ryan (2004) notes ongoing experimental studies of rubber cage collar systems indicating that some accepted models of cage loadings may need to be reconsidered.

Notes:
Highly resilient to wave forces with long service life (more than 10 years); relatively good impact resistance. Effective and proven net hanging system. Variety of configurations possible. Relatively cheap at higher volumes. Most widely used commercial offshore system. Some designs may be subject to considerable wear and tear as a result of wave action. Net volume can be decreased in some cases quite considerably as a result of deformation due to tidal and wind driven current flow. Stanchions may cause problems in flexible cages – twisting, turning. Relatively expensive at lower volumes. Limited walkway access. Top net and feed systems difficult to place. Large service vessels necessary. Some Bridgestone cages will hold 500 tonnes of fish.

Some cages are now submersible. PolarCirkel submersible cages can submerge to depths ranging from 3m to 20m, depending on the depth of the frame mooring, e.g. if the depth of the frame mooring is 5m, the cage can be submersed to ~10m. The depth of the frame is determined by local conditions and by water depth. Submersing the cage can be done quickly, taking 15-20 minutes (no more less than 20 minutes with fish in cages).

The PolarCirkel submersible cage is basically an evacuation system and the cage is designed for feeding when it is at the surface. However, work is in progress on feeding methods and feed types for submerged cages. PolarCirkel submersible cages operate in Norway, Sweden, Taiwan, Italy, Turkey, Canada, Chile, Oman, the United Arab Emirates and China.

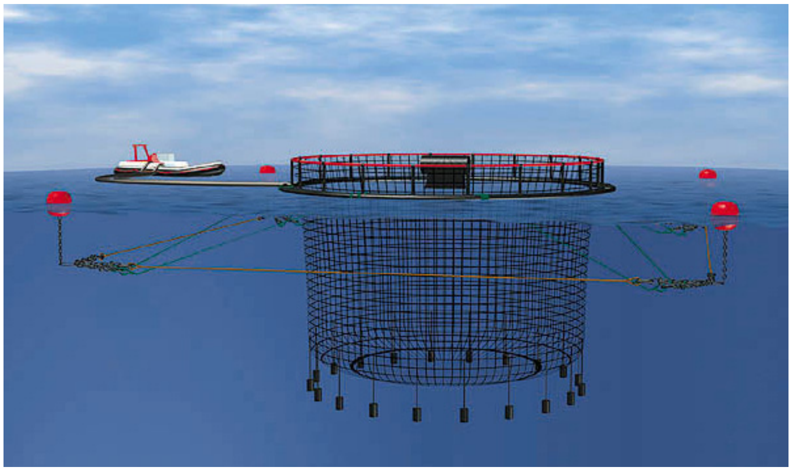

Figure 23 polarCirkel® submersible cage is designed for sites subjected to rough weather, pollution, algal blooms, wide temperature variations, fouling, icing of cages and drift ice (http://www.polarcirkel.com).

Figure 24 polarCirkel® partly submerged (http://www.polarcirkel.com)

6.1.6.2 Surface gravity cages with submerged collar

Description:
Circular buoyancy collar system with the cage net bottoms attached to a rigid framework

Examples:
Canadian Aquaculture Engineering Group (AEG – Canada) (see Figure 25).

Construction:
Now in development, this system uses relatively conventional plastic collar cages arranged in flotillas of six or eight cages which are attached at their base to a rigid framework. A novel design of single point mooring secures both the framework and a feed barge.

Volume(s):
Each cage would be 100m by 15m providing a volume of about 12,000 m^3. A farm unit would be between 72,000 m^3 and 96,000 m^3.

Cost m^{-3}*:*
Not available.

Status:
In development. Anticipated first deployment in 2006 in Bay of Fundy, Canada. Feed systems (circa. 200 tonnes capacity) are being developed in parallel to dovetail with proposed mode of operation.

Notes:
Original deployment was proposed for 2004. The latest information from the company is that they intend to deploy the first system in autumn 2006 with a view to stocking the cages in spring 2007. The cage system has been designed by a company with considerable practical fish farming experience in the difficult conditions which prevail in the Bay of Fundy. The designers have adopted a low cost approach using a combination of available technology with innovative mooring design. The integrated feeding system is designed to operate automatically and feeds the fish underwater (http://www.aquacultureengineeringgroup.com).

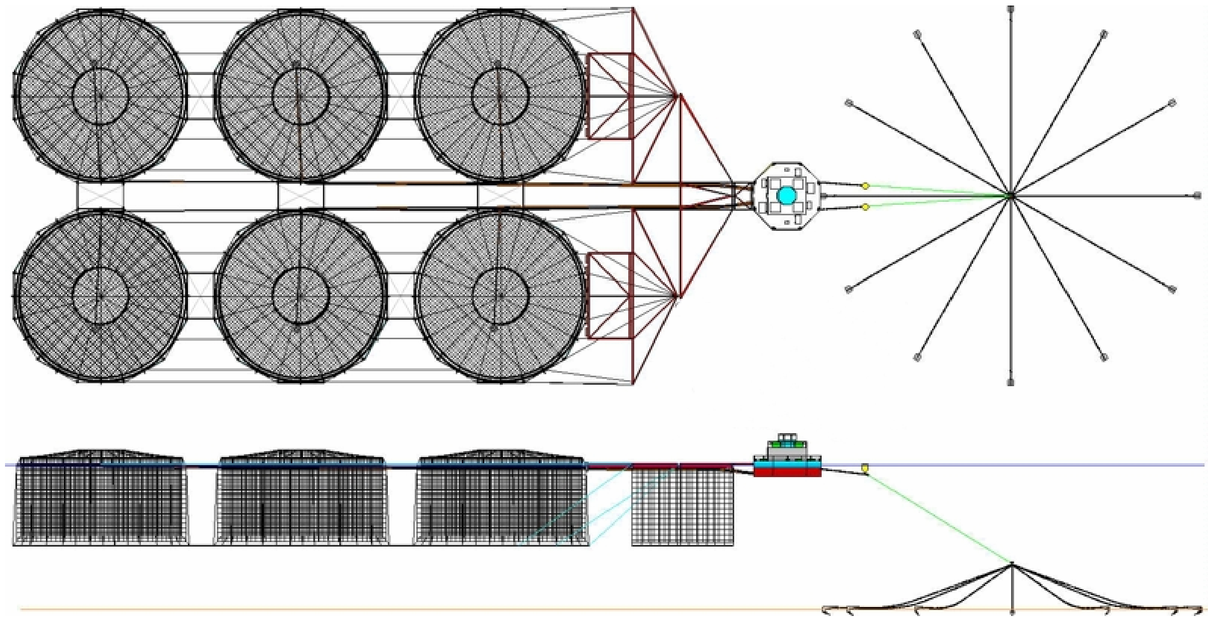

Figure 25 Canadian Aquaculture Engineering Group (AEG – Canada). Above – plan view of six cages attached to framework and through a feed and service barge to a single point mooring system. Below – side view of system (http://www.aquacultureengineeringgroup.com).

6.1.6.3 Semi submersible gravity cages

<u>*Description:*</u>
Semi submersible cages –these systems are designed with rigid framework elements providing only limited movement or volume change in response to external loads. The structure is semi-submersible, with the net suspended beneath in the gravity configuration. Service facilities such as feeders etc. may be incorporated into the system making them more or less self-contained.

<u>*Examples:*</u>
Farmocean (Sweden), Storm Havbruk (Norway) (see Figures 26, 27 and 28).

<u>*Construction:*</u>
Farmocean example: Rigid steel construction consisting of a collar and radiating series of tubular steel spokes which are angled upwards, meeting at the centre to form a platform which supports a maintenance pod and feed silo. The collar and spars contain buoyancy elements which can be partially flooded to allow the cage structure to raised and lowered. By locating the main volume of the cage well below the surface it avoids the worst effects of storms. Mooring is by means of a fixed three point system. The net is attached to the inside of the framework; its shape is maintained with a steel sinker tube suspended from the main pontoon ring. Industrial zips are used to allow access inside the cage and can be used to allow panels to be replaced. The feed silo has a three tonne storage capacity.

<u>*Volume(s):*</u>
Farmocean **-** 2500 - 6000 m^3, with 3500 m_3 as the most popular size.

<u>*Cost* m^{-3}*:*</u>
Farmocean - The cost of the system is relatively high, being over £50 m^{-3} for the 3500 m^3 cage. Storm – not available.

Status:
Farmocean **-** Over 40 systems have been installed, mainly in Northern Europe and the Mediterranean. Farmocean cages were deployed in Scotland but with limited success due to high capital costs, low cage volume and difficulties with husbandry.

Notes:
Farmocean - first cage was launched in 1986 and has now been tried and tested in a variety of situations and in severe conditions. Proven long service life. Stable holding volume. Good stock performance. High capital cost. Poor access for harvesting. Difficult to change/clean nets. Limited surface area when submerged for surface feeding. Complex steel structure; needs corrosion protection, regular maintenance. Production capacity 150 tonnes. Farmocean – operational current speeds of up to about 1.0-1.3 ms^{-1} and waves heights of 10 m, maximum recommended operational depth of water 100m (http://www.farmocean.se, October 2003 – in Ágústsson, 2004).

Storm - cages reported as undergoing trials in Norway in 2003, have capacities of up to 900 tonnes of fish. No new information available (http://www.marineconstruction.com – March 2006).

Figure 26 Farmocean cage deployed (http://www.farmocean.se).

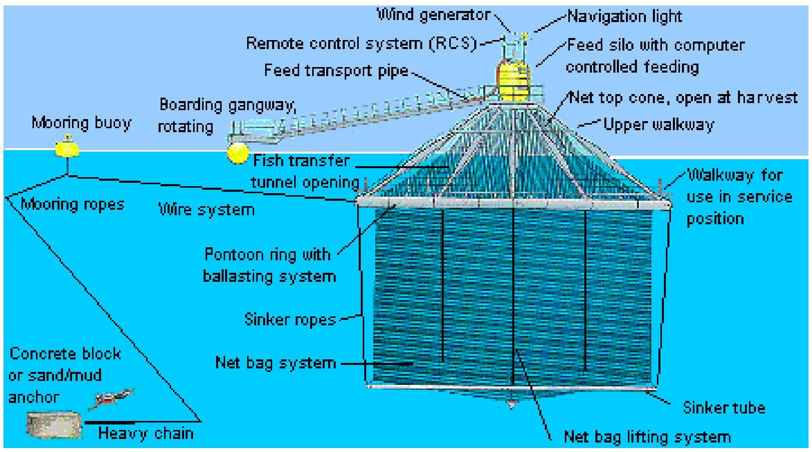

Figure 27 Diagram of Farmocean cage showing complete system in side view (http://www.farmocean.se).

Figure 28 Storm cage deployed (http://www.marineconstruction.com)

6.1.6.4 Fully submersible cages gravity cages

<u>*Description:*</u>
Fully submersible cages – as for semi submersible cages, but are capable of full submergence.

<u>*Examples:*</u>
SADCO Shelf (Russia), Trident (Canada), Marine Industries Investments (MII) (Israel) (see Figures 29 and 30).

<u>*Construction:*</u>
A rigid tubular steel framework from which the net and weight ring are suspended. The cage system is fully submersible and is fitted with a feed silo.

SADCO - The current models (SADCO-500/1200/2000) are based on a ballasted upper steel hexagonal superstructure carrying the net which is kept in shape by a lower sinker tube. The frame also carries a feeder with volume of 1500l (SADCO 50), which can operate underwater.

Trident - Developed on the East coast of Canada to deal with icing in winter. The cage is fully submersible and has a near spherical (ellipsoid) geodesic format frame made from simple foam-filled tubular frame units of high tensile marine aluminium (6063T6) connected with specially designed structural ties. The net is attached directly to the frame. As with other geodesic structures, this offers structural simplicity, good strength to weight ratio and an efficient volume. Very limited structural deformity under load ensures that the net within is kept taut at all times. The cage has variable buoyancy and in normal use can also be sited with the upper part at the surface.

Marine Industries Investments - Essentially a submersible rigid steel conventional cage system but with rigid underwater frame to maintain net shape. Cage clusters can be secured to a simple single point mooring via a service buoy which controls submergence and feeding functions. The system was designed to function in conjunction with an offshore trawler which could provide all infrastructure needs and the cage could be operated either in semi-submersible or fully submersible modes.

Volume(s):
SADCO **-** Volumes available are up to 2000 m^3,
Trident - Sizes available are 1000, 4000 and 5500 m^3, the design could be scaled up to 10,000 m^3; MII - Clusters of up to 8 cages in one unit are possible, with cage volumes of either 1700 or 3400 m^3.

Cost m^{-3}:
SADCO - Costs not available. Bugrova (1996) – best estimates for operational costs of SADCO. Trident, structural simplicity suggests that provided materials costs are acceptable, basic system costs could be moderate. Costs not available.

MII – costs not available.

Status:
SADCO - The cages have been installed in the Caspian, Black and Mediterranean seas, and a commercial unit is currently operating in the SW Italian mainland. The more recent designs are considered to be better built and more reliable, though problems have been noted in efficient feeding in submerged mode. A central-column design with a hexagonal outer ring (SADCO 2500), otherwise similar in concept to the Ocean Spar Sea Station had also been successfully tested at model scale.

Trident – current status unknown.

MII - cage system was developed in Israel in response to the severe conditions in the eastern Mediterranean (Ben-Efraim, 1996). Brought into pilot scale production at the end of 1993 and first stocked in 1995. Current status unknown.

Notes:
SADCO - Russian design which has evolved since the early 1980s (Bugrova, 1996). Early models of ~100 m^3 in the Caspian and Black Seas (SADCO-100) had successfully withstood severe storms with 12 m waves. Although this system has been deployed successfully in extreme conditions, it has high capital cost and relatively low volume (4,000m^3). Like the Farmocean cage this system has an integrated feed silo. These cages may be produced in 8,000m^3 and 12,000m^3 versions (http://www.sadco-shelf.sp.ru).

Trident - Performance in test and initial commercial scale production has been claimed to be good, with excellent physical response and good control of fouling. One cage was reported to have withstood wind speeds of 80-120 km/h (22-33 m/s) and breaking waves of >3.5 m, whilst two thirds submerged. Rotation of the cage allows self cleaning of fouling organisms. A telemetry/feeder unit spar buoy concept has also been developed to operate the systems remotely in open ocean conditions.

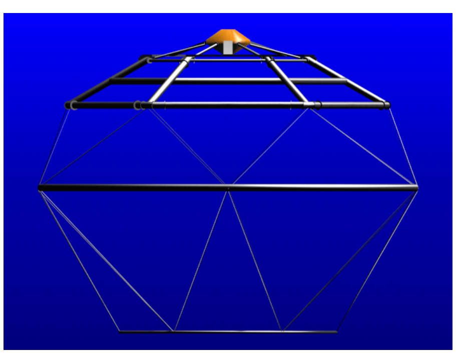

Figure 29 Diagram of structure of SADCO Shelf (http://www.sadco-shelf.sp.ru)

Figure 30 SADCO Shelf deployed at surface (http://www.sadco-shelf.sp.ru)

6.1.6.5 Anchor tension cages and enclosures

Description:
Net cage or "enclosure" volume is maintained by a tensioned mooring system

Examples:
Ocean Spar net pens (US); Maris Platform Fish Ranch (MPFR) (UK) (see Figures 31, 32 and 33).

Construction:
Ocean Spar net pens - This is a flexible system where the hexagonal net enclosure volume is maintained by being tensioned against six vertical steel spars. A variety of configurations are possible from squares to polygons of 200 m circumference.

MPFR - A web-like net structure with the enclosure volume maintained by a system of specialised spar buoys tensioned in a subdivided triangular or composite hexagonal cage. The cage structure is designed to be semi-submersible. Similar spar buoy designs have been utilised in the offshore sector.

Volume(s):
Ocean Spar net pens - Cages of 15,000m^3 and 20,000m^3 have been deployed, cages of up to 60,000m^3 could be produced.

MPFR - each triangular cage enclosure would be 400,000m^3, joined to form an hexagonal "farm" of 2.4 million m^3.

Cost m^{-3}*:*
Ocean Spar net pens – no published costs available.

MPFR - estimate costs of £3.90m^{-3} for 100,000 unit to £1.30m^{-3} for a 2.4 million m^3 unit.

Status:
Ocean Spar net pens - Cages have been installed in various locations in the USA, and systems and sub-components well tested in a number of locations and species usages. Cages of 15,000m^3 and 20,000m^3 were deployed in Ireland where a variety of logistical and operational difficulties were experienced. Whilst some of the difficulties in feeding, net cleaning, harvesting and removal of mortalities could be addressed by changes in working practices, together with innovative equipment design, there are cage design issues that need to be addressed also (see Ryan, 2004). This system has not been widely installed commercially.

MPFR - Developed as a concept only. The MPFR concept of very large submersible 'tension' enclosures in open waters, was registered for patents, in August 2002. The designers are seeking UK Government funding to support a pilot scale deployment.

Notes:
Ocean Spar net pen - system retains 90% of net volume even in strong currents (up to 1.75 ms^{-1}). Low surface visual impact. Good predation resistance due to taut nets. Relatively simple design. Potentially cost effective, especially in larger sizes. Top net can be attached. Relatively complex mooring system. Net changing less straightforward than in bag systems. No walkway access. Feeder cannot be installed. Needs large service vessels.

MPFR – conceptually, two or more 2.4 million m^3 farms would be developed in the no fishing zone alongside existing offshore oil or gas platforms. Whilst the designers envisage use of the system for large scale offshore aquaculture production, the underlying principal is to use such a system for "ranching" to produce marine finfish for wild stock restoration. Designed for up to 10kgm^{-3} – equating to around 4,000 tonnes of fish per enclosure. The MPFR enclosure is claimed to be capable of: use in exposed ‘open ocean’ locations with significant wave heights and sea swells; submerging by up to 30m, or more, below the surface; maintaining volume in up to 2 or 3 knots, or more, of current. Large vessel could moor up to buoys to access the enclosures. The mooring system is described as “simple” but requires winches on a nearby fixed or floating ‘platform’. Alternatively submersible winches could be mounted on the buoys and powered remotely. The designers are experienced in the offshore oil and gas sector and are confident that a range of technologies from this sector can readily transposed for fish farming operations.

Many of the caveats attached to the Ocean Spar are likely to apply to the MPFR design. The scale of this proposed MPFR design is larger than any system developed thus far and its size will generate technical and management challenges. The designers are considering the use of new and novel technology to overcome some of the foreseen issues. It is proposed that net cleaning will be minimised by submersion and the possible use of metallic netting, antifoulants and/or electrification. It is considered more economic to employ remotely controlled cleaning machines, than to replace the net enclosure when the drag force limit is reached. Remotely Operated Vehicles (ROVs), or Autonomous Underwater Vehicles (AUVs) are proposed for inspection, repair and maintenance – very little in-situ maintenance or repair is anticipated although it is proposed that net repairs will be made by unmanned vehicles. The designers anticipate that the enclosures will be capable of remaining in place for several years and the logistics of handling the nets will fall within the compass of available fishing gear technology. Concentrating the stock for transfer, grading, harvesting and treatment would possibly involve the use of internal sweep nets, or ROV’s and sound. ROV’s and underwater video equipment “Eyeballs” would be used to monitor stock and remove moribund and dead fish. The designers also anticipate disease will be minimised because of the use of “low” stocking densities and the open ocean environment. The designers quote various proposed options for feeding. The designers working hypothesis is that the enclosures will not need to be accessed by personnel because of the proposed scale of operation, coupled to the use of remote and automated systems for husbandry and farm management.

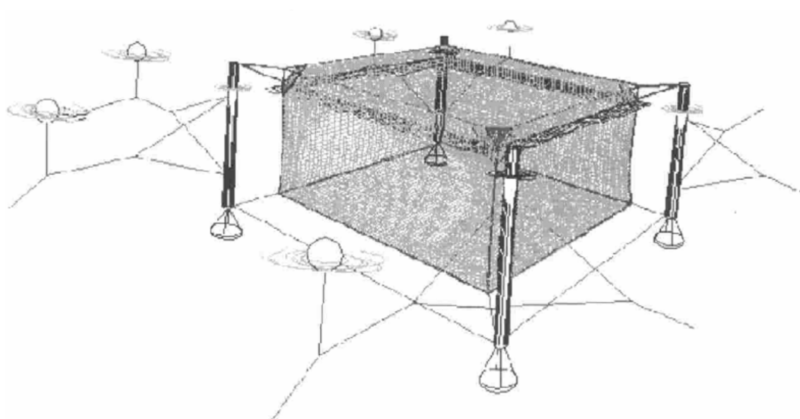

Figure 31 Diagram of Ocean Spar net pen – note the spar bouys at each corner, against which the net is tensioned.

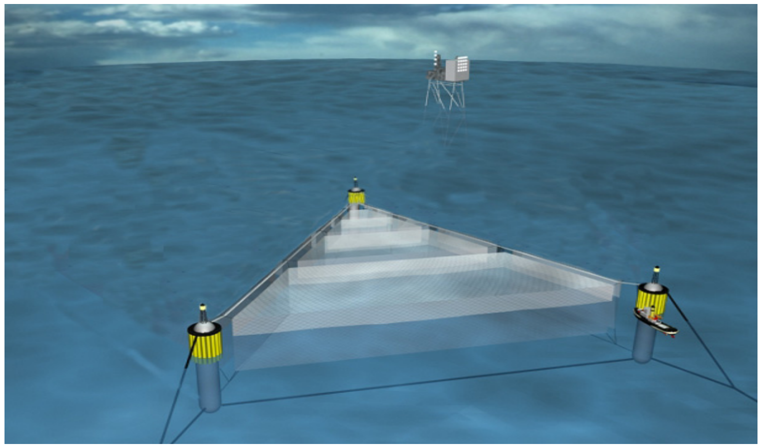

Figure 32 Diagram of one segment of the conceptual MFRL design. This enclosure system would be by far the largest single cage unit if deployed (courtesy of Maris Fish Ranches Ltd.)
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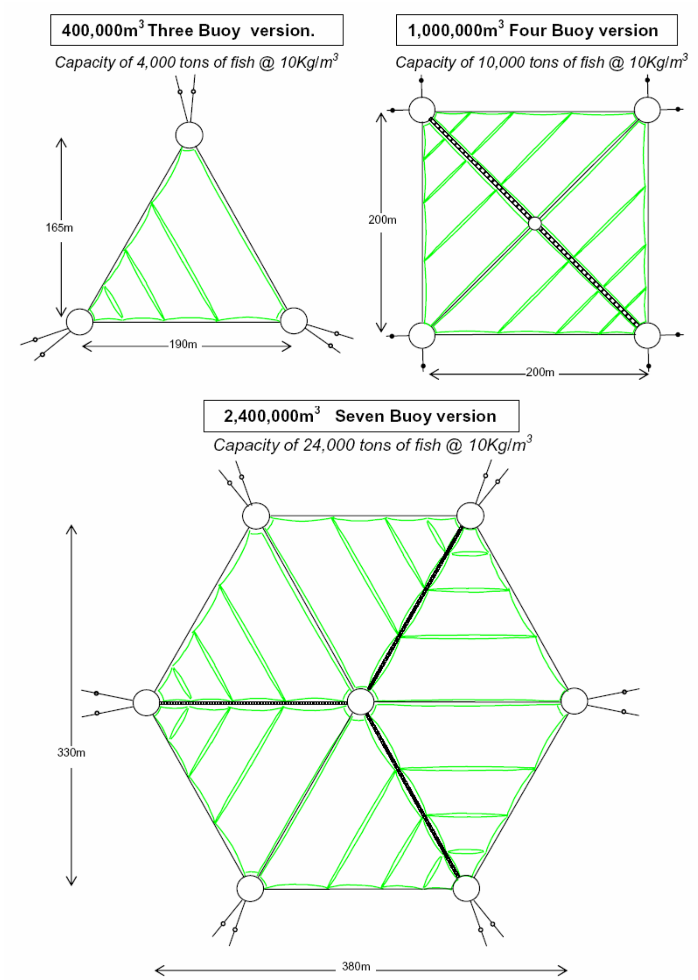


Figure 33 Diagram showing plan view of various deployment options for the proposed MFRL design (courtesy of Maris Fish Ranches Ltd.).

6.1.6.6 Semi-rigid cages

Description:
Net cage volume is maintained by ropes used to connect rigid steel components

Examples:
Submersible Ocean Spar Sea Station (US) (see Figure 34).

Construction:
The net enclosure volume is maintained by being tensioned over a framework consisting of a central steel spar inside a circular steel collar joined together with tensioned non-stretch ropes. The steel tube vertical spar provides buoyancy and distributes loads to the net and the circular tubular rim via radiating framing lines. A further version of the design has two tubular rings, vertically separated, to increase the depth and volume of the system. Nets and framing lines use high specification polymer fibres which maximize strength while reducing sectional dimensions and system drag. The tubular steel rim maintains the net's shape and also has ballasting capabilities. The cage can be fully submerged by means of varying the buoyancy in the central spar, unlike the Farmocean, some of whose volume remains above surface. A small platform on top of the central spar allows for feeding, access and monitoring. Larger systems could potentially incorporate feeding storage and service controls, but these would have to be fully waterproofed were the system to retain its fully submersible options. The system is moored at the central spar, allowing either for single point or fixed configurations.

Volume(s):
The standard production model has a volume of 3000 m^3. Larger versions with 6-8000 m^3 are planned.

Cost m^{-3}*:*
Estimated cost based on the 3000 m^3 units is between £20 and £30 m^{-3} installed.

Status:
These cages have been deployed in Class 4 sites in Hawaii and off the coast of New Hampshire (largely on an experimental basis). Production systems have been tested in the N W Atlantic with flatfish, and a unit was been installed in Cyprus in 1998 (Gace, 1998, pers. comm. – in Scott and Muir, 2000).

Notes:
Limited to small cage volumes of 3,000m^3 and perhaps up to 6,000m^3. Operational current speeds of 0.8 ms^{-1} are reported (http://www.oceanspar.com, November 2003 – in Ágústsson, 2004). In currents of 1 ms^{-1}, over 90% of cage volume has been recorded as retained. The Sea Station cage can withstand continuous waves of over seven meters, can be submerged and raised in fifteen minutes, and can be easily towed to a new location, due to the rigidity and stability of the structure. Harvesting is also said to be straightforward by means of inverting the bottom conical section of the net. However, this system is not yet widely proven in commercial practice although more practical designs may evolve. There still seems to be a reliance on diver operations for some routine tasks. Efficient feeding and net changing may be difficult.

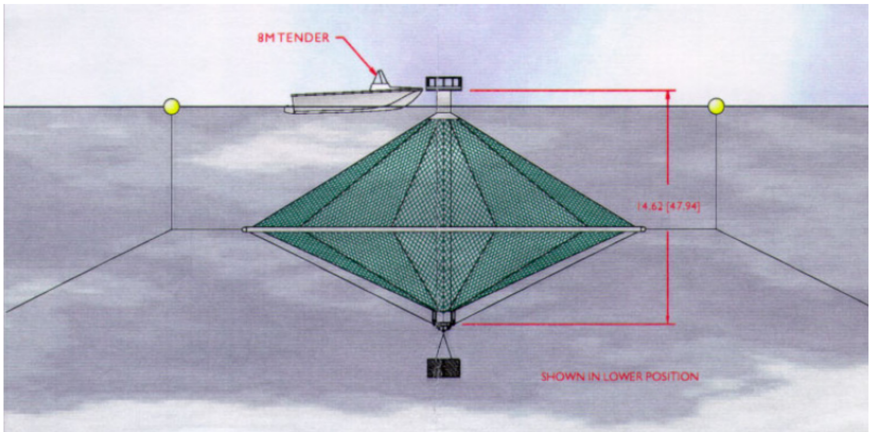


Figure 34 Diagram of Oceanspar cage submerged (see - http://www.masgc.org/oac/gallery01.html and http://www.oceanspar.com/pictures.htm)

6.1.6.7 Rigid cages

Description:
Net cage volume is maintained by rigid structural components made of steel or other materials

Examples:
*Surfa*ce - Aquasystem 104 (Norway); Pisbarca, Cripesa and Cultimar - Marina System Iberica (Spain); Cruive – Lithgow Group (Scotland), (see Figures 35, 36 and 37).

Construction:
A solid frame work is used to support the net enclosure. Rather than attempting to be wave compliant, these systems are designed to withstand wave action, and are generally of large, massive structure, normally of steel construction, with varying degrees of ballasting, sometimes with concrete. Most designs incorporate feeding systems, cranes, stores, generator, and staff quarters, etc. Some systems are also self-propelling.

Pisbarca and Cripesa - designed around a hexagonal-plan individual modules, with vertical cylindrical flotation columns and a steel frame deck, on which can be housed various superstructure elements, including lifting gear, stores, accommodation units.

Cultimar - Floating platform built in a steel tubular structure consists of 9 cages 50m X 50m square cages.

Cruive - The standard structure is 45 m x 45 m and offers 4 cages of 20 m x 20 m by 20-25 m deep. The structure can be equipped with feed stores, cranes, net handling equipment, etc.

Volume(s):
Aquasystem 104 - A ship-like structure 126 m long by 32 m wide designed to support 12 cage enclosures of 2000 m^3 .

Pisbarca and Cripesa - An hexagonal steel structure with 7 cages producing 250 tonnes per year and giving a total volume of 10,000 m^3 .

Cultimar – Total estimated volume of 18,000m^3.,

Cruive - Total volume of 32,000-40,000 m^3 .

Cost m^{-3}*:*
Aquasystem 104 - Estimated capital cost of £2.5 million, installed cost £100 m^{-3}.

Pisbarca and Cripesa - The cost is understood to have been around £1.5 million equating to £150 m^{-3}.

Cultimar – Cost unknown.

Cruive - Cost per unit volume is comparatively reasonable due to the large holding volumes. The basic steel structure without cranes, feed stores, etc., but with 20m deep nets and moorings, costs around £16 m^{-3}.

Status:
Aquasystem 104 - First installed in Ireland, but in extreme weather conditions problems were encountered with net failure and the company responsible closed down. The cage was later transferred to Spain.

Pisbarca and Cripesa - The system has been deployed in Spain and continues to operate, but is commonly extended by surrounding the central system with simpler and lighter cages, with the aim of using the main platform as the service unit for the complete system.

Cultimar – The System has been deployed in Spain and appears to be in operation near Barcelona.

Cruive – Only tested in Scotland and initial trials suggested that without further technical development, its potential may be limited in exposed locations.

Notes:
Typically the most expensive type of offshore system, although this extra cost has to be assessed against the facilities which are incorporated and would otherwise have to be supplied at additional cost. The uptake of such systems commercially has been limited. Some systems have suffered from structural or net failure. Surface based systems tested in exposed conditions have not performed well with nets being destroyed due to the rigidity of the framework.

Aquasystem 104 - production potential of 500 tonnes per unit.

Pisbarca and Cripesa - production potential of 250 tonnes per year. Although the design can incorporate full support facilities some deck-mounted units have been damaged and have subsequently been removed.

Cultimar - production potential of 450 tonnes per year. The freeboard of the platform can be changed easily to adapt it to the different sea climates, this is done through the ballasting system of its vertical columns. Over the platform deck there are four cubicles that hold the power generator, the biological laboratory, the feeding warehouse and the crew dormitory. The platform is moored in open sea, a couple of miles from the shore, the mooring system is designed to resist the most critical storm conditions.

Figure 35 Cruive off-shore fish farm from Campbeltown Developments Ltd., cage system (After Scott and Muir, 2000)

Figure 36 Fish farm platform from Marina System Iberica – the Cultimar (http://www.msicom.net)

Figure 37 Fish farm platform from Marina System Iberica – Cripesa. The basic structure is the same as the Pisbarca but incorporates an automated feeding system (http://www.msicom.net)

6.1.6.8 Rigid cages spheriodal

Description:
A plastic framework designed to support a spherical net enclosure with an optional landing platform which rotates around the main axis of the cage.

Examples:
Submersible - Byks OceanGlobe (Norway) (see Figures 38-42).

Construction:
OceanGlobe is a sway anchored (single point moored) ellipsoidal, closed and submersible offshore farming structure with a continuous centre pole, a surrounding horseshoe shaped working and docking platform whish is an integral part of the anchoring of the structure. The frame of the cage is constructed of plastic pipes whilst the centre pole and other components of the structure are made of steel. The cages can be subdivided internally to provide two or three smaller enclosures.

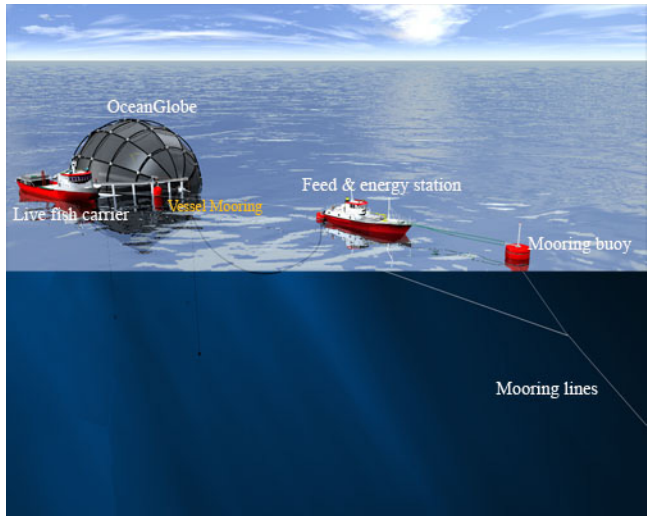
Volume(s):
Largest volume expected to be 40,000 m^3, but 23,000 m^3 and 12,000 m^3 units are also proposed.

Cost m^{-3}*:*
Not yet available.

Status:
A full scale deployment will take place in 2006. The project is fully financed (http://www.byks.no – March 2006).

Notes:
This appears to be a carefully thought out design concept which has been extensively modelled and tested in the laboratory. Aspects of fish husbandry and management together with the need for specialised support vessels has been considered from a practical perspective. The cage system is designed to operate in a variety of semi-submerged or fully submerged modes down to

Figure 38 Diagram of OceanGlobe in service position at the surface (http://www.byks.no)



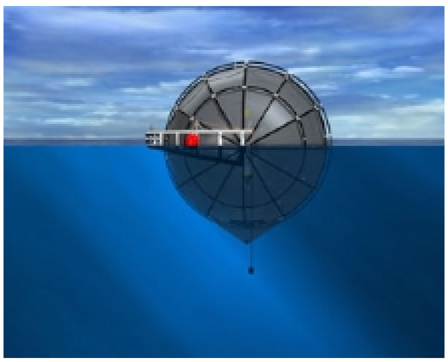


Figure 39 Position 1: Semi-Submerged is a working position. Personnel can safely do all the necessary work operations above the water from a horseshoe shaped working platform. Hence, no divers are needed

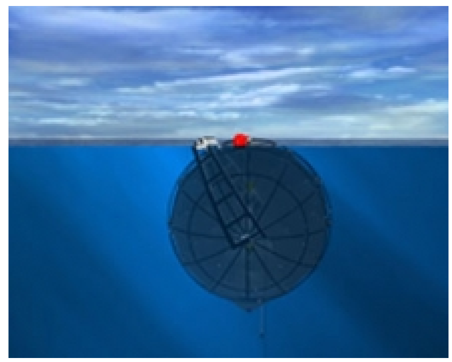


Figure 40 Position 2: Surface position or iceberg position, is the normal breeding position for all anadromous species. Approximately 10% of the system is above surface, so that the fish can get air from an air dome in top of the cage.

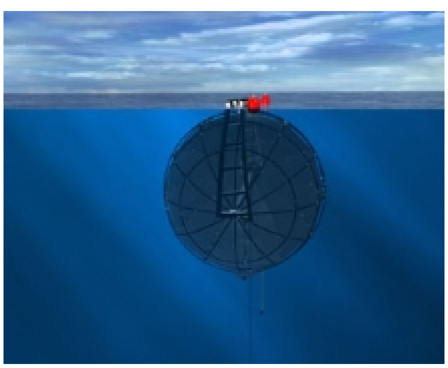


Figure 41 Position 3: Submerged position, is the normal breeding position for the majority of fish species, including most marine species. The cage is completely submerged. The working platform functions in this position as rest buoyancy.

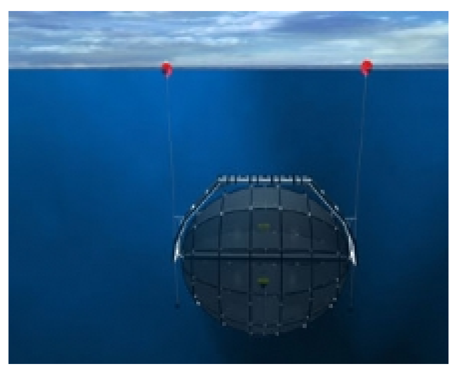


Figure 42 Position 4: Extreme-submerged, this position occurs in extreme situations like algae invasions, unfavourable temperatures, storms/typhoons etc. or if the breaded fish naturally belongs in the deep water

20m. For periods of prolonged submergence, an air pocket has been included in the design to facilitate the need for anadromous species such as salmon and trout to inflate their swim bladders. The largest cages could theoretically hold up to 1000 tonnes of fish. (Ytterland and Kvalheim, 2005). OceanGlobe is designed to withstand a significant wave height of 14m (and wave period 16s), including waves with a total height of 30m, and current velocities of up to 1.5 m/s (Ytterland pers comm. – in Ágústsson, 2004).

6.1.6.9 Tension-leg cages

Description:
A small floatation collar at the surface with no mooring lines attached is connected to a much larger subsurface net enclosure volume maintained by a ring at the bottom to keep the tension legs spaced.

Examples:
RefaMed (Italy) (see Figures 43 and 44).

Construction:
Effectively an inverted gravity cage, tension leg cages avoid many of the problems of high stress loadings caused by the forces of wind and wave action at the surface acting upon moored cage collars. Tension leg cages are moored at their base and thus flex with the prevailing current.

RefaMed - a circular plastic positive buoyancy supporting frame, held below the net pen, is held in place by vertical mooring ropes. These mooring ropes stem from concrete blocks on the sea bed which rise to the buoyancy ring, above which the net is kept in suspension by subsurface buoys. An upper conical section gives access from the surface via a traditional plastic cage collar. The design is simple and there are no metal structural components. The upper cone can be removed and the cage raised for harvesting and net changing, etc., utilizing a full size plastic collar brought temporarily to the site.

Volume(s):
RefaMed - available in a variety of sizes up to 10,000 m^3.

Cost m^{-3}*:*
RefaMed **-** Based on 1996 estimates, the cost for a unit of 4 x 6000 m^3 cages installed with nets would be around £10-14 m^{-3}.

Status:
RefaMed - cages of 4,000m^3 have been deployed in the Mediterranean and 15,000m^3 cages should be possible. The system has been tested in Norway and Sicily, and cages have also recently (from Scott and Muir, 2000) been installed in Taiwan.

Notes:
RefaMed - In storms or strong currents, the cage responds automatically, the net being pulled under the water and thus reducing wave and current forces. Considered to be a simple, relatively cost effective design. Combines features of conventional operation with storm protection. Net volume reduction no greater than 25% in currents/storms. Feeding should ideally be done subsurface, requiring separate feeding systems, due to limited area on surface. However, these cages are currently limited to areas with relatively small tidal ranges because they are fixed to the seabed. Trials with modified nets near the surface may, at least in part resolve this issue.

Figure 43 Diagram of RefaMed cages deployed.

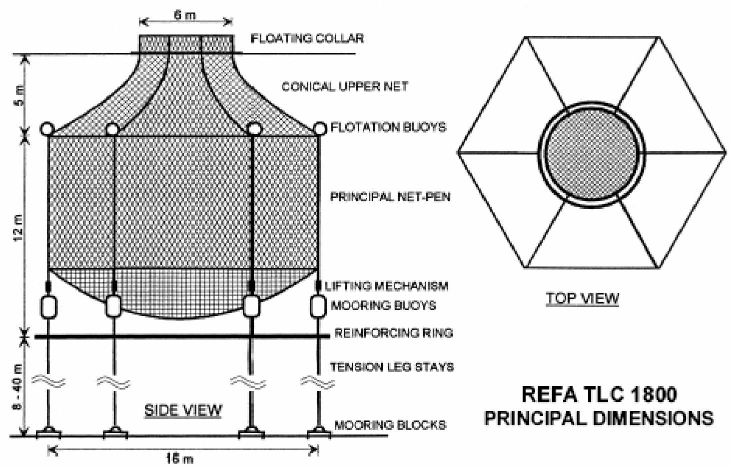


Figure 44 Lateral and plan views of RefaMed cages

6.1.6.10 Untethered cages

<u>*Description:*</u>
Large unmoored, self contained structures supporting massive net enclosures designed to drift in the open ocean. Large nets or semi rigid cages suspended beneath floating platforms or ships.

<u>*Examples:*</u>
Surface - Ocean Drifter *(US);* Semi submerged structures - Izar Fene Semi submersible tuna ship (Spain), Izar Fene Semi submersible platform (Spain) (see Figures 45, 46 and 47).

<u>*Construction:*</u>
Ocean Drifter - Still at the concept stage, this is essentially a massive Ocean Spar Sea Station design which incorporates a surface platform for personnel and feed storage. Whilst the cage is designed to drift, a propulsion system is also envisaged. Without the need for moorings, structural loads would be reduced, potentially requiring less robust and cheaper production.

Izar Fene Semi submersible tuna ship – Concept involves using a semi-submersible hull, 189m long and 56m wide with fish tanks in the hold and a rigid cage suspended beneath the hull.

Izar Fene Semi submersible platform.

<u>*Volume(s):*</u>
Ocean Drifter - 64,000m^3 cages

Izar Fene Semi submersible tuna/restocking ship – volume appears to be dependant on configuration ~ 130,000 m^3.

Izar Fene Semi submersible platform – 47,000 m^3.

Cost m^{-3}*:*
Ocean Drifter - unkown.

Izar Fene Semi submersible tuna ship – unknown.

Izar Fene Semi submersible platform – unknown.

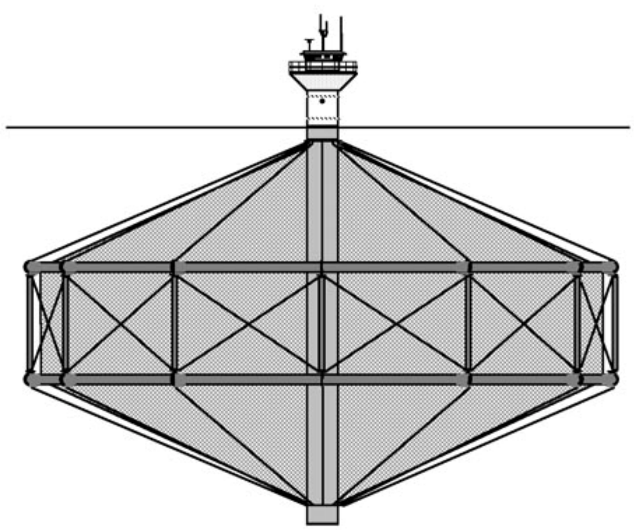
Status:
Ocean Drifter – concept only.

Izar Fene Semi submersible tuna/restocking ship – concept only.

Izar Fene Semi submersible platform - concept only.

Notes:
Ocean Drifter - These massive cage enclosures are designed to drift in the open ocean - presumably in International waters, avoiding some regulatory and licensing requirements, whilst deriving the benefits of clean water and, potentially, reduced incidence of disease.

Izar Fene Semi submersible tuna/restocking ship – The idea would be to use this vessel to hold live tuna at the point of catch and on-grow them during their passage to the main markets in Japan. The design has also been altered with a view to using it as a self contained unit for restocking marine fisheries. The Izar Fene Semi submersible platform is a similar concept to their vessel.



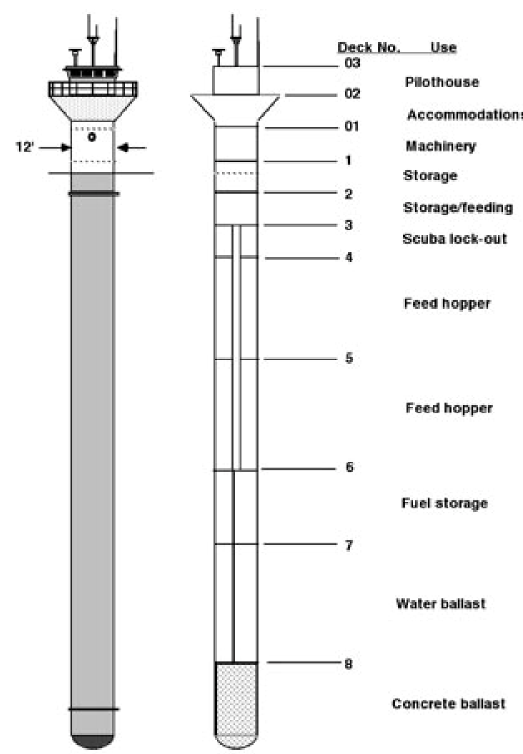


Figure 45 Diagram of lateral view of cage system and detail of central spar of the conceptual Ocean Drifter cage.

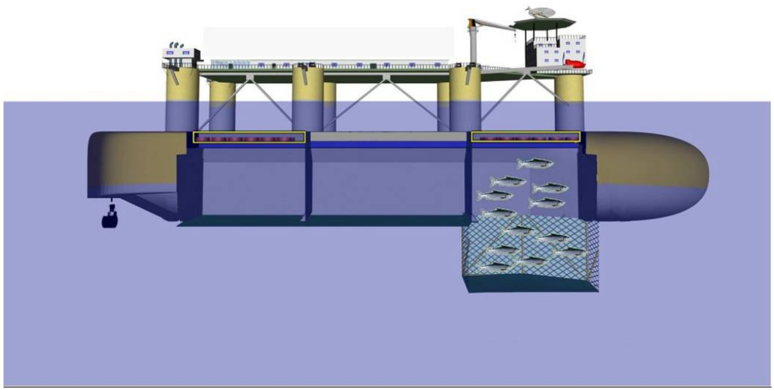


Figure 46 Izar Fene Semi submersible tuna/restocking ship – concept.

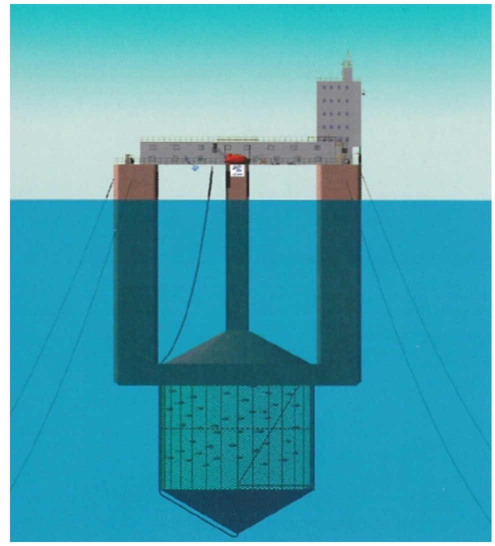


Figure 47 Izar Fene Semi submersible platform - concept

6.1.7 Biological considerations

6.1.7.1 Influence of enclosure size shape and depth.

We have largely focused on the physical considerations of the offshore environment and the various engineering solutions that have been developed either in concept or reality to on-grow fish in enclosures or cages in these conditions. Fundamental to the ability to cultivate fish economically, is the need to provide them with optimal conditions for growth. Whilst considerable advances have been made with respect to the husbandry of the most commonly cultivated species, there is remarkably little information in the published literature regarding, for example, the optimal depth, current speed, light regime etc. that would be applicable to cultivating fish in offshore conditions. The following discussion assumes that the fish being cultivated are suited to the prevailing water temperature and water quality regime.

According to Beveridge (2004), there has been little systematic study of the relationship between the size of aquaculture systems and growth and production. Through trial and error it has been found that larger shoaling and pelagic species, such as salmon, tunas and yellowtail, grow faster in cages with larger surface areas (Nose, 1985). Trials conducted in Norway, comparing production of salmon in 50m and 90m circumference cages, showed that fish in the larger structure grew faster, that there was improved feed conversion and less feed loss, lower mortality and a reduction in the incidence of sexual maturation (Guldberg *et al.*, 1993). There is little evidence, however, that cage area affects less active species such as cod for example, to the same degree. Similarly, the extent to which the surface area effect relates to stock density is unclear. Little is known about depth. Studies of anadromous, air-breathing fish maintained in tanks have shown that there are depth related energy and time costs associated with travel for aerial respiration (Kramer, 1983; Bevan and Kramer, 1986). The swimming depth of salmon is influenced by a number of factors, the relative importance of which varies with season and time of day (Juell, 1995). Commercial trails in Norway showed that Atlantic salmon will utilise cage depths of up to 35m (Huse and Holm, 1993). Little is known of the relationship of cage area and depth as influences on fish behaviour and growth etc. (Beveridge, 2004).

6.1.7.2 Light

The duration (photoperiod) and intensity of light changes daily and seasonally. The spectral quality of light changes with depth in water. The rate at which daylight is absorbed and attenuated by different bodies of water varies greatly and depends on the amount of dissolved and suspended matter in the water.

Photoperiod is considered as the most important factor that entrains animal rhythms, including the reproductive cycle. Several studies have addressed the effects of artificial lighting on fish reared in sea cages (Bayarri *et al.*, 2004). In Atlantic salmon, continuous light exposure affects growth and sexual maturation (Endal *et al.*, 2000), whilst additional night time illumination reduces grilsing and plasma melatonin (Porter *et al.*, 1999). The fact that cage lighting influences fish performance has been exploited in fish aquaculture, where artificial lights are used to submit fishes to shorter or longer day lengths, and thus manage to advance or delay gonad maturation and spawning time (Bromage *et al.*, 1995). If maturation can be delayed or inhibited until marketable size is reached, fish farmers may avoid reductions in growth and deteriorations in flesh quality that accompany sexual maturation (Bromage *et al.*, 2001). In the case of sea bass, photoperiod manipulation, among other techniques, has been used to control the reproductive status by delaying sexual maturation (Zanuy *et al.*, 2001) and/or altering the spawning time (Carrillo *et al.*, 1995). Controversial results showing that cage lighting may (Atlantic salmon [*Salmo salar*], Porter *et al.*, 1999) or may not (Atlantic cod [*Gadus morhua*], Porter *et al.*, 2000) significantly reduce the nocturnal melatonin rise, suggest inter-species differences or insufficient light exposure, which points to the need for a better understanding of the effects of light on the neuro-endocrine system of fish (Bayarri *et al.*, 2004).

Aspects like light intensity, spectrum, and orientation must be taken into account when designing an effective lighting system for sea net cages and enclosures. It has been shown that intensities of less than 20 lux should be avoided, as they may lead to inconsistent results. The spectrum of lights should be preferably as close as possible to that of natural light, rich in all visible wavelengths (Bromage *et al*., 2001). As Bayarri *et al*. (2002) demonstrated with regard to European sea bass, light should be directed downwards, mimicking sun light, as the pineal gland which responds to light is located at the top of the brain and receives light from above.

Many species of fish are visual feeders and therefore require a certain amount of light to be able to recognise and capture food efficiently (See Feeding below). Inefficient feeding will lead to lower productivity and is economically and environmentally unacceptable.

Offshore conditions will dictate that cages may need to be submerged for extended periods to depths more than 20 meters to avoid adverse conditions. Artifical light sources will therefore be required to optimise productivity for some species. The necessary power and cabling infrastructure required to provide light of appropriate intensity and quality will need to be incorporated into offshore farm designs and is likely to be of particular importance to submerged operations (see Fernö *et al.*, 1995; Juell, 1995; Oppedal *et al.*, 1997; Oppedal *et al.*, 1999; Oppedal *et al.*, 2001; Jeull *et al.*, 2003; Juell and Fosseidengen, 2004).

6.1.7.3 Currents

Current velocities in coastal marine areas typically range from 0 ms^{-1} at slack water to in excess of 0.25 ms^{-1} at some sites during ebb and flood tides (Beveridge, 2004). Offshore, currents vary seasonally and tend to be of a lower velocity – a few tens of cms^{-1} below the level of wind driven effects (http://oceancurrents.rsmas.miami.edu/atlantic/north-atlantic-drift.html - March 2006).

Good water exchange through the nets is essential for the replenishment of oxygen and removal of waste metabolites. Currents also influence fish behaviour, affecting social higherarchies, growth and growth disparities amongst stock (Phillips 1985; Leon 1986; Jobling *et al*., 1993; Jobling 1995) and reportedly flesh quality (Beveridge, 2004).

Increasing current velocity can permit increased stocking densities but for some non-tensioned gravity cages, increased drag results in deformation of the net and up to 25% reduction of the net bag volume, although this can be minimised by correct net weighting and tensioning, horizontal forces acting on the cage bag may increase two to six fold (Tomi *et al.,* 1979 and Loland 1993a and 1993b). In addition, fish may expend excessive energy to maintain station, adversely affecting production. In practice, ebb and flood tidal currents in the range of 0.1-0.6ms^{-1} and mean tidal currents of 0.03-0.2ms^{-1} have been found to be satisfactory; sites where currents exceed 1ms^{-1} are not generally recommended (Braaten and Saetre, 1973; Chen 1979; Chua and Teng 1980; Kerr *et al.*, 1980; Ikenoue and Kafuku 1988; Rudi and Dragsund 1993; Turner 2000b). Excessive currents impose additional dynamic loading to the cage, supporting structures and moorings, may adversely affect fish behaviour and contribute towards food losses from semi-intensive and intensive operations. Although optimal current regimes within cages are likely to be species specific, it has been suggested that constant flow rates inside cages should not exceed 0.02 ms^{-1} (equating to <0.03 ms^{-1} outside the cage) above this, energy expended on swimming increases significantly and growth and survival are adversely affected (Beveridge, 2004).

In the offshore environment, accelerated water flows due to wave motion can be considerable as can wind driven current speeds. Similarly, persistent current flows can exceed 1ms^{-1}. Whilst wave motion and wind driven effects reduce with depth, current flows are less affected and will act throughout the water column. Given the capacity to submerge the fish stock below the worst effects of wave and wind, the critical biological factor in terms of site selection is therefore current speed.

6.1.7.4 Feeding

Most commercial marine fish farms, cultivating carnivorous fish, use dry pelleted feeds. Over the last 40 years considerable research effort has been invested in optimising diets with a view, for example, to maximising growth rates, protein sparing, feed conversion ratios, minimising waste, and more recently replacing fish oil and fish meal with vegetable substitutes. As the cost of dry feed is significant, ranging from 25-50% of farm costs, it is important that feed and feeding strategies are carefully matched to a range of operational parameters, including species, life stage, temperature, light, fish behaviour etc.

Offshore cage farms are likely to be of large scale in terms of cage or enclose volume and of significant depth or will be submersible. To ensure maximal and even growth within the stock, the fish must be fed to satiation as often as possible. The feeding strategy must ensure that as many of the stock as possible are able to access food. Cages have relatively smaller surface to volume ratios, which means that food can be rapidly lost from the cage by currents. The depth of the net enclosure may also dictate that light levels may be low. Environmental conditions, especially light levels change with the season and the time of day, affecting vertical fish distribution. Atlantic salmon prefer to feed at low light levels, provided the feed pellets are easily accessible and detectable (Petrell and Ang, 2001). Stocking density, body size and age affect social structure and access to food (Anras *et al.*, 2001).

Given the projected size of the cages and enclosures proposed for offshore use, it would seem likely that feeding strategies and indeed the feeds themselves may need to be considered. To minimise grading requirements, feed delivery systems will need to be carefully deployed to reduce competitive interactions and minimise the impacts of dominance hierarchies within the captive stock. With deep cages and submerged cages, feeding at depth may be required.

The need to store and distribute feed in bulk is a significant undertaking in the inshore environment with farms producing a few thousand tonnes of fish per year. The salmon industry has seen the development of feed barges (for review see Beaz Paleo *et al.*, 2000). Barges hold between 50 and 400 tonnes and can deliver up to 80 tonnes of feed a day. Some of the more sophisticated barges are self propelling, with cranes, pumps, silos, generators and fuel tanks. They have centralised feed distribution systems that deliver feed directly to the cages via blowers. Compressed air feeders, operated from a boat have been used to distribute feed at large offshore cages. Pressurised water systems have also been used to deliver feed from a centralised unit to individual cages along pipelines. However, this system has caused problems with low growth rates and mortalities attributed to loss in food quality (see Beveridge, 2004)

Interactive feedback feeding systems are now widely available and monitor uneaten food or fish feeding activity, to modulate feeding rate with appetite (for example see Foster et al., 1995; Juell *et al.*, 1993; Ang and Petrell 1997; Myrseth 2000). Cameras, infrared detectors and Dopler systems are used to detect uneaten food pellets. Through a variety of feedback systems, feeding is stopped and in more advanced systems software algorithms have been developed to determine the optimal time and ration for the next feed. The advantage of these systems over less sophisticated demand feeders is that they measure the response of the whole cage population and thus help to reduce differential growth.

Integrated interactive feedback systems would need to be an integral part of any offshore feeding strategy, not only because they reduce manpower requirements and can operate automatically, but because in commercial situations, these systems have been shown to reduce Feed Conversion Ratio (FCR) values by an average of 20% (see Myrseth, 2000).

Artificial lighting regimes have been shown to modify diurnal feeding patterns, extend feeding periods, reduce early sexual maturation, increase growth and improve FCR and flesh quality in salmon and cod (Oppedal *et al.*, 2001). The capacity to operate controlled light regimes offshore, particularly if fish are to be cultivated at depth, will need to be considered. Feed losses due to currents washing pellets out of cages, together with lower feeding efficiency due to poor visibility at depth may be a significant consideration for offshore aquaculture operations. In addition to underwater feeding systems, novel feed formulations may be required to ensure that the feed is optimal in terms of visualisation, density and nutritional stability.

6.1.7.5 Disease and disease management

Whilst the incidence of disease may be lower offshore because of the potentially lower prevalence of pathogens coupled to possible advantages of lower stocking densities, fish welfare considerations dictate that there will be a need to protect and treat fish for a range of common diseases. Vaccines are available for some conditions, some of which can be administered prior to stocking at sea. A limited number of in-feed treatments are also available, for sealice for example. Other therapuetants must still be administered as bath treatments. Conducting such treatments in the offshore may require novel techniques and working practices to overcome significant logistical constraints imposed by the scale of the cage or enclosure and prevailing sea conditions.

Physical damage to fish in offshore conditions is likely to occur through acute trauma resulting from the effects of wave forces and through more chronic effects such as scale loss and fin damage caused by abrasion with the more robust net materials that may be required.

Disease management and control is a significant issue. Early detection is essential to minimize losses, maintain productivity and prevent the spread of disease. Much disease management in inshore sites is based on daily observation of fish behavior and performance, together with regular disease testing regimes as part of routine on-farm monitoring and under statutory regulation (see for example http://www.cefas.co.uk/fhi/legislation.htm). Access to cages and stock in the offshore situation is likely to be more limited, particularly if cages and enclosures are to be submerged. Whilst remote observation using submersible camera's is entirely feasible, the capacity to effectively observe and detect the often subtle changes in stock which alert the experienced fish farmer to a disease problem may not be. Novel approaches to monitoring stock health remotely may be required, together with prophylactic treatments which provide long term protection against disease.

6.1.7.6 Stocking strategies and densities

Large scale intensive fish farms usually adopt a strategy of stocking high numbers of young fish that are gradually transferred to other cages as they grow. As well as being a more cost effective use of facilities, this practice tends to lead to better and more even growth rates and facilitates disease control through separation of year classes (Beveridge, 2004). It is anticipated that for some species the minimum size for juvenile fish to be stocked in offshore systems may be much larger than for inshore cages (ICES WGEIM, 2002).

In Scotland salmon are typically being farmed at densities of between 15 and 20kgm^{-3} and cod at 15 kgm^{-3}. Cod can be held at higher densities but the main UK producer farms to an organic standard for which this is the maximum permitted. A maximum working density for salmon is normally 20kgm^{-3} with typical maximums of 17-19 kgm^{-3}. More recently some farms are stocking densities as low as 11 kgm^{-3} (E. Gillespie, pers. comm. – SEPA).

Stocking densities have been a subject of much debate (FSBI, 2002) from both an environmental and fish welfare perspective. It is generally acknowledged that "higher" stocking densities for some species – Arctic charr and halibut being notable exceptions, (see Jorgensen *et al.*,1993; FSBI, 2002) have a negative impact on fish welfare, through increases in stress, injury and disease (see Beveridge 2004 and FSBI 2002, for additional references). Recent experimental evidence for salmon and trout, however, suggests that water quality relative to stocking density is of overriding importance with dissolved oxygen levels serving as a reasonable proxy to indicate appropriate levels of stocking (J. Turnbull pers. comm.; North *et al*., *In Press*).

One of the advantages advanced for prosecuting aquaculture in the offshore environment is that fish could be farmed profitably at lower densities by virtue of the economies of scale. However, there is limited scientific data available to define what densities are optimal in terms of fish welfare and economics. Current stocking levels are largely based on the experience of farm managers and fish performance. Fish welfare indices are under development for trout, salmon and more recently cod, in the context of intensive inshore cultivation (see above). Appropriate stocking densities in the offshore environment are likely to be different, if the environmental and operational characteristics of these farms varies from those inshore. For example, it could be argued that if, as a result of better water exchange and lower pathogen levels, higher stocking densities may be acceptable. Conversely, difficulties in applying prophylactic treatments and treating diseased fish because of the scale of the cages and the prevailing weather conditions may encourage cultivation at lower densities.

Stocking densities will obviously relate to total biomass per unit area and volume of the cage site which in turn will have implications for feeding requirements, medication and farm discharges. All these factors may have different levels of significance depending upon the way the farm is designed and operates. As discussed elsewhere in this report, a single point mooring will allow discharges over a larger area of seabed, facilitate greater water exchange and potentially reduce the effect of current on the stock. Stocking densities in these systems could potentially be higher than in cages or enclosures of similar volume which are or fixed orientation. It seems inevitable that offshore cage structures will be submersible. Depending upon the depth at which the cage operates relative to the seabed, if may be necessary to reassess stocking densities and discharge consents based on the operational depth of the cage if, for example, there are significant differences in temperature and current regimes at different depths.

6.1.7.7 Monitoring water quality

It is generally accepted that for offshore fish farming operations, much automation and telemetry will be required to overcome the constraints outlined in other sections of this report. Monitoring fish welfare will be paramount to ensure that production is maximised and losses minimised. Fish welfare studies are increasingly pointing towards the need to maintain optimal water quality, particularly with respect to oxygen saturation (J. Turnbull pers comm., North *et al.*, *In Press)*. There are a variety of automated devices for monitoring water quality parameters such as temperature, dissolved oxygen, ammonia and chlorophyll levels etc. If direct husbandry of the stock is to be largely limited to observation through remote cameras, it would be desirable to look at other ways of remotely detecting or predicting fish welfare. Remote monitoring of a wide range of physical and chemical parameters will undoubtedly be required to provide real time information and analysis of critical aspects of structural status and performance of the farm. Much of this technology exists or could be developed in a relatively short time frame. Unless deployed on a large scale, the cost of these developments could, however, be significant. In many respects, the success of offshore farming may actually hinge on their use as part of routine management in such an environment – the use of this technology is likely to be a prerequisite, rather than a desirable addition.

6.1.7.8 Fish handling - Crowding

Prior to grading, treating and harvesting, the stock is generally crowded in order that the fish in can be corralled, netted and or pumped to another net or receiving vessel. In some of the larger enclosure-type cages the logistics of conducting this exercise has clearly not been fully considered from a practical perspective (see Ryan, 2004). It is possible that novel use of acoustic attractants could be employed by entraining the stock to respond to such stimuli, but the author is unaware of this technique being used in a commercial context.

6.1.7.9 Fish handling - Fish transfers

There are numerous well tested means of transferring fish from well-boat to cage, cage to cage etc. These techniques involve either netting the fish, using fish pumps or some form of swim through system whereby the cages are physically joined together. As a general rule, such practices should be conducted in a way which minimises stress (see for example Flagg and Harrell, 1990; Cabello, 2000).

Whether fish transfers are taking place for the purposes of stocking, grading, harvesting, net changing or maintenance etc., it is clear that, as yet, there is little operational experience and not a great deal of experimental evidence to support practical developments for offshore operations in UK conditions. Assuming that the logistics of such practices will be significantly different to those conducted inshore, by virtue of scale and prevailing sea conditions.

6.1.7.10 Fish handling - Grading

To maintain optimal growth performance fish are graded at regular intervals and separated into populations of similar size. Monitoring the size and weight of stock is an important part of routine fish farm management. Video and hydroacoustic systems for monitoring fish size, distribution and biomass within cages are already in use in intensive fish farming (see for example: Treasurer 2002).

From a fish welfare and practical perspective, grading can be a stressful and time consuming task even in the relatively quiescent inshore environment. Increasingly, in-cage "passive" grading systems are being used in Scotland and Norway, which involve crowding the fish to a greater or lesser extent with a mesh or grid of a given size which allows fish smaller than the apertures to pass through thus separating them from fish too large to pass through the apertures. Passive grading systems tend to be operative and time dependant (I. Keene-Smith, pers. comm.) and are probably not a practical way forward for offshore developments. Well boats are increasingly being used for grading and for combining grading with sea lice treatments for example (I. Keene-Smith, pers. comm.). The use of specialised service vessels is likely to be the most flexible solution for offshore fish farms, with platform based grading where appropriate.

6.1.7.11 Fish handling – Medication and treatment

Although some prophylactic treatment is given to fish before they are stocked into seacages, there will inevitably be a requirement to treat them with some form of medication during the on-growing phase. Whilst some in-feed medications are available, some chemotherapeutants can only be administered through bath treatments. In inshore areas this process is normally conducted using tarpaulins which are slung beneath the cages to contain the treatment and ensure that it is administered at the correct dose for the appropriate duration. In offshore conditions tarpaulins are unlikely to be practical, but as noted above, well boats may be an option. As large scale commercial offshore aquaculture has not yet taken place to any extent, the disease issues which may accompany it, have not received much attention – save for the general and largely anecdotal assumption that there will be "less" disease. Containing and treating fish, particularly in some of the larger offshore cage and enclosure systems is likely to require careful consideration and should, from a welfare perspective, be a central consideration for the designers of such systems.

6.1.7.12 Fish handling – Removal and disposal of dead fish

Removal of dead and moribund fish is a routine part of farm management, even in the absence of disease outbreaks. It is important that the numbers of fish removed is recorded for disease monitoring, stock density, performance and insurance purposes (Beveridge, 2004). Various methods have been developed for the removal of dead fish either manually through netting or with divers or more recently, by being pumped out through the base of the net. Whilst the later technique may lend itself to some offshore cage structures, it is unlikely to be applicable to some of the larger tension leg and submersible systems. The designers of the Maris Platform Fish Ranch have proposed the use of ROV's to perform this task but this technique has not been demonstrated practically or with respect to its economic viability.

Within UK Territorial waters (within 12nm of the coast), a raft of national and EU legislation and regulation now covers the disposal of fish and fish waste (see for example: http://www.scotland.gov.uk/Publications/2005/03/20717/52862#1 – March 2006). Some dispensations are available for remote locations such as the Highlands and Islands of Scotland, because of inaccessibility to appropriate disposal facilities. However, given that this legislation stems from the EU it is likely that these regulations or amendments there of, could apply beyond the 12nm limit and out to the UK EEZ (See Section 4 of this report).

6.1.7.13 Fish handling – Harvesting

All fish slaughter methods are more or less stressful (FSBI 2002). Whilst a number of slaughter methods are currently permissible, it is likely that in the future, smaller fish will undergo electrical stunning as described by Robb and Roth (2003), with specific modifications for dealing with marine species. Larger fish will either be stunned individually as part of a controlled but automated process, either electrically, percussively or with spiking. The manner in which fish are killed has both welfare and flesh quality implications (see FSBI, 2002 for additional references). In the inshore, after a period of fasting, the fish are crowded and either netted or pumped out of the cages after which they are killed, iced and transferred to onshore processing facilities. Cages can be towed to shore or fish transported live in well-boats to facilitate harvesting nearer to the processing plant.

In the offshore situation, the arrangements for harvesting and possibly processing fish at sea will depend on the type of cage structure, distance from shore, accessibility to a suitable platform and facilities. In line with the systems approach, careful consideration needs to be given to the development of offshore farms, if the promised economies of scale are to be properly realised. The scale of farming operation needed to support a viable processing unit either seagoing or platform based needs to be considered as part of the overall package.

6.1.8 Operational logistics and management

Routine fish farm operations will need to be carefully considered in offshore conditions to maximise profit, within the constraints imposed by operating remote from shore bases, using high levels of automation in harsh and often extreme weather conditions. All aspects of transport, stocking, grading, feeding, medicating, harvesting, net cleaning and maintenance will have to be considered with reference to these operational constraints. Whilst some of the knowledge and technology already exists or could potentially be adapted, the cumulative risks of moving aquaculture into the offshore remain considerable with currently available equipment and expertise.

Fish welfare remains a primary concern both ethically and in terms of profitability which is underpinned by the need to minimise production stress and disease, maximise food conversion efficiency and increase product quality and marketability. The well being of staff and, in particular, their health and safety is likely to be a significant commitment offshore.

6.1.8.1 Transport

All goods and services supplied to offshore facilities will need to be transported by sea or air. For large fixed installations, helicopter transfer of staff and high value, low volume, low weight goods is possible and may be economically viable for farms of sufficient scale. Farms without access to the necessary facilities for helicopter transfer will be reliant upon access via suitable vessels. For economic reasons, fish, feed and other bulk loads will need to be conveyed by sea.

Whilst many transport functions will not necessarily be time critical, the capacity to supply feed regularly and in the reverse direction, fish to order, will demand reliable transport infrastructure capable of operating routinely in the weather conditions which prevail in UK offshore situations. For existing oil and gas installations, the cost of transport compared to overall operational costs is probably not significant. This would probably not be the case for offshore fish farms, without significant economies of scale and or cost sharing between offshore operators.

For species such as cod and salmon, juvenile fish would probably be supplied from land based hatcheries and freshwater on-growing sites. Well-boats developed in Norway for transporting live fish are used extensively in the marine cage farming industry. Disease regulations and logistics have lead to the production of purpose built vessels capable of transporting up to 50 tonnes of live fish. Smolts can be transported in such vessels over many hundreds of kilometres, but low speeds must be maintained during long sea passages and rough weather can result in mortalities (Tseng 1983).

In some sectors, cages are used to tow fish to on-growing sites. In southern Australia, small bluefin tuna are captured by perse-seiners and towed 400km to cage production facilities in Bridegestone-type or plastic Norwegian (flexible collar) cages. Each cage can hold 165t of fish which are towed at less than 2km per hour – the passage normally taking 5 weeks to complete. If cod cages are towed the fish ball up in the cage and they are crushed, in contrast to salmon which swim against the flow (See Woo *et al.*, 2004).

Air transport, particularly using helicopters is common practice in the salmon industry, with tanks holding 20,000 smolts suspended beneath the helicopter and travelling for periods of up to several hours (Beveridge, 2004).

The optimal means for transporting juvenile fish to offshore sites (beyond current operational distances) would need to be carefully considered as part of a detailed cost model. Much like many of the operational criteria discussed in relation to offshore cultivation, this process needs to be considered as an integral part of the production and marketing operation.

6.1.8.2 Maintenance

Given the prevailing conditions in the offshore environment, it seem inevitable that maintenance requirements will be higher than in the inshore environment, even if the structures and materials used are stronger and of higher specification. However, maintenance tasks considered as routine inshore are unlikely to be so offshore.

Technology exists to allow real time monitoring of some structural components, ranging from remote visual inspection using ROV's and cameras, to stress and load sensors capable of providing a range of structural performance data. The depth and nature of the maintenance tasks involved will dictate whether repair or replacement can be carried out *in situ* by divers or ROV's or whether retrieval and surface or land-based maintenance will be required.

6.1.8.3 Maintenance - Fouling

Fouling reduces effective mesh size and increases mesh surface area. As a result, the flow of water through the cage is reduced – reducing dissolved oxygen supply and the removal of metabolic wastes. Increased resistance to water flow can cause distortion of the net enclosure, reducing cage volume. The overall increase in the weight and drag forces impacting on the pen structure can lead to increased wear on moorings, cage collar components and lead to structural failure and net damage. The rate, scale and community structure of fouling organisms depends upon location, depth, temperature, nutrient and current regimes. As a rule, the longer a structure is immersed the more fouling occurs. It is of most significant and rapid in marine sites with slow currents (See Costa-Pierce and Bridger, 2002 for example).

Net changing and cleaning is a widely used management strategy for fouling. A range of usually copper based antifoulants are also used to treat nets in various ways and can significantly reduce fouling for up to about 6 months, depending upon local conditions and the time of year the nets are deployed. Biological controls, particularly herbivores, have been stocked alongside the species being cultured. Sea urchins were found to effectively remove fouling from salmon cages, but tended to be restricted to the base of cages only (Cook, 1999). No commercial farms cultivating temperate species use biological controls.

Some fouling resistant cage materials are available such as PE netting which is inlaid with copper wire. This material is at least twice the cost of conventional netting and is reported to have a limited life of perhaps two years – after which the net must be replaced or treated with conventional antifoulant. Rigid cages have also been deployed using materials resistant to fouling, such as galvanised steel, PVC coated wire and copper or copper nickel compounds. Fouling of polypropylene or metal alloy rigid mesh cages is much slower than on net cages. Consequently, cleaning can be conducted less frequently. However, metal alloy antifouling solutions are likely to be relatively expensive (see Beveridge 2004 for a list of relevant references).

Rotating cage designs can be used to control fouling and facilitate easy cleaning. Semi submersible cages such as the Farm Ocean design can be cleaned with out net changing. It is likely that fully submersible cages, particularly those operated at depths where light levels restrict algal growth, will have less fouling than those at or near the surface. However, commercially available designs of semi-submersible and rotating cage cost several times more per unit volume than conventional cage designs.

Net cleaning will still be required in the offshore environment if unsustainable drag forces and structural failures are to be avoided. In conventional cage bag designs, nets are physically changed, either manually or through semi-automated processes. Some of the “offshore” cage designs utilise industrial zip technology to facilitate access to cages and the changing of net panels. Typically the nets are either allowed to dry and the fouling removed through pressure washing or increasingly, net washing machines are used. *In situ* automated cage cleaning devices have been developed but have proven ineffective, leaving a surface that is only partly cleaned and as a result, rapidly re-colonised (Hodson *et al.*, 1997).

6.1.8.4 Maintenance - Moorings

Loadings transferred to mooring lines vary depending upon current and wave conditions, cage design and number of lines employed (see Beveridge 2004). Currents can produce significant drag forces, but long period waves tend to result in considerable cyclical peak loads lasting for only a fraction of a second. In practice, mooring requirements are over specified that may lead to over-damping of heave and surge motions (Frediriksson *et al.*, 2003).

Two types of mooring system are in general use – single and multiple point. Single point moorings are less common, but allow the cage structure to move in a circle. Multiple point moorings are used to secure the cage(s) in a chosen orientation. Single point moorings use less cable and chain than multiple point moorings, and by design, adopt a position of least resistance to the prevailing wind wave and current forces, thus reducing inter-cage and torsional forces at linkages (Linfoot and Hall 1987, Thoms 1989). Lien (2000) also states that single point moorings reduce the significant net deformation experienced with conventional mooring systems. Single point mooring systems have been used successfully in Norway to moor large offshore cages. In addition, single point moorings distribute waste over a much larger area than cages fixed within a multipoint mooring system. Beveridge (2004) estimated a 20 to 40 fold increase in the area over which waste would be distributed, with Goudey *et al*., (2001) suggesting that there could be up to a 70 fold reduction in waste deposition per unit area of sea bed. Mutlipoint moorings do however use less space per unit area of cages and are thus favoured in restricted inshore sites. Both multipoint and singe point mooring systems are used or proposed for offshore cage designs.

There is considerable expertise in mooring design and maintenance in the maritime and offshore sectors and the assumption is that maintenance of mooring systems in the offshore environment is well practiced. The costs of deploying and maintaining mooring systems offshore may need to be considered carefully, in the context of the overall economic viability of farming fish in this environment. The flexibility offered by a single point mooring system, coupled to a dedicated service vessel/feed silo and a submersible cage system would seem to be a practical way forward particularly, where space is not limiting but water depth is considerable.

6.1.8.5 Risk and Insurance

If offshore aquaculture is to become a reality, potential investors will need to be convinced that they can generate an attractive return. The scale of investment required for offshore aquaculture is likely to be significant and the financial and practical risks will be higher than inshore. Insurance costs are typically between 1 and 10% (assumed as 3% for the purposes of economic evaluation in this report) of the value of the insured stock, depending upon the extent of the cover and the risks involved (Beveridge, 2004). In assessing risk, insurers will take into account:

- Site and Environment
- Species and Health Management
- Farm Design
- Personnel
- Redundancy – backup systems
- Financial Security

Sunderaland Marine Mutual Insurance is well known for insuring aquaculture operations worldwide. This company underwrites offshore tuna on-growing in Australia and is clearly aware of the need to cover offshore developments generally (Kennedy – Farming the Deep Blue presentation 2004). Royal Sun Alliance-Aquarius and Willis also offer aquaculture insurance and at least one company producing offshore cages offers lease arrangements which include full risk insurance (Maris Ltd., pers. comm.).

7. CONCLUSIONS

This assessment attempts to provide an overview of the biological, technical, legal and economic considerations involved in offshore finfish cultivation in UK waters. It should be recognised that this is a diverse and complex subject area which is at an early stage in its development. In considering the clearly defined topic areas covered in this report it is important to understand that the emphasis applied to the factors discussed may be significantly different if viewed in the context of other sectors such as shellfish production or indeed the potential for co-culture. This study has not been designed to address the wider socio-economic issues which might apply to offshore aquaculture development or engaged in any stakeholder analysis. Nor has the study made any detailed assessment of the way offshore aquaculture could be integrated at an EU or wider international level. However, aspects of this assessment are relevant to other aquaculture sectors in the UK and elsewhere and many of the underlying constraints and opportunities highlighted are likely to be similar.

The focus of our analysis has been with respect to the culture (ongrowing) of finfish such as salmon and cod (treated as proxy generic species A and B respectively) in offshore enclosures (including cages or net pens). The assumption is that the fish will be fed and ongrown to harvest within such enclosures. We have not attempted to assess the concept of fish ranching, where the fish are retained in a specific area and would generally be expected to feed on naturally available food and or supplemented feed. Nor has the deliberate release of fish for the purposes of stock restoration (conservation, mitigation or enhancement) been considered. There are significant biological, environmental, economic and legal question marks related to this practice. A wealth of literature and experience pertinent to marine stock restoration exists and the authors would urge separate consideration of this evidence (see for example: Howell *et al.*, 1999).

7.1 Financial and Economic Perspective

This study has presented a wide range of information about economic modelling, including:

- ‘Core’ models for two species options, based upon a suit of realistic assumptions
- A series of sensitivity analysis, varying a range of assumption categories, for both species

The implications of economic implications for offshore aquaculture presented in this report are based on the results of the modelling and the experience of the author. Further economic modelling in the future, particularly after more pilot-scale practical experience has been gained, may prompt significant changes in the approach to the issues discussed below.

7.1.1.1 Species Choice.

Two generic types of species (A and B) have been defined and modelled, based on their speed of growth in the farming situation. It would be tempting to exclusively consider these as species such as Atlantic salmon and Atlantic cod respectively, but this is unnecessarily restrictive and may not be appropriate in the long term. Atlantic salmon growth rates in modern aquaculture are allegedly much faster than they were when farming began in the 1970’s, largely as a result of selective breeding and improvements in feeding and nutrition. It is almost certain that the growth performance of any ‘new species’ (which might be typified by Species B) would improve over several generations of domestication. The key point for offshore aquaculture, however, is that it must make good returns on capital right from the start. A faster-growing species (e.g. Species A) is more likely to achieve the necessary returns at this stage of the industry’s development.

7.1.1.2 A Compelling Economy of Scale for Existing Operators?

There is not yet sufficient detail about likely operating costs in offshore conditions to be certain of anything, but the current modelling exercise does not suggest any particular ‘economy of scale’ advantage for such large installations. Even modelling across a range of unit pen costs from £5.00 to £1.00 m^{-3} only improves the core Species A IRR from 14% to 17%. It would appear that there is no overwhelming economic advantage of the offshore system concept in terms of replacing existing inshore pen aquaculture, unless such inshore systems became more expensive due to as-yet unforeseen additional regulatory or other costs. On the other hand, there is also apparently no major economic obstacle to considering such offshore installations in the future, if there is demand for more productive capacity on a global basis, and if the species choices and economics work as well as some of the more optimistic sensitivity scenarios in this study might suggest.

7.1.1.3 Sales Price.
It is very clear from all the sensitivity analyses that the likely sales price of the fish being grown is the most important variable. It will therefore be essential for would-be investors in offshore aquaculture to have a very clear market-led vision, and a robust marketing plan. The challenge for any future large scale investment in this type of technology is overall trend of sales value for the main aquaculture species in the world – a downward trend, as production volumes increase. However, there are still several species of marine finfish being farmed around the world with market values in excess of £3.00 per kg, which would appear to be a viable price level for offshore aquaculture (assuming the salient technology issues are resolved).

7.1.1.4 Global Production.
Aquaculture is now very much part of the global food supply sector and there are unlikely to be many ‘regional niche opportunities’ which would not be subject to market challenge in the future. While there is still unused production capacity for inshore pen aquaculture in any regions of the world (e.g. Chile, parts of Norway and possibly Scotland), it is difficult to foresee how global finfish production volumes, for some of the major species such as Atlantic salmon, would decline such that offshore aquaculture became compellingly interesting for investors. However, the introduction of ever more rigorous environmental regulations in some of these regions might lead to exactly such a change in emphasis.

7.1.1.5 Scale of Operation.
The economic modelling in this study has followed the same presumption as that made by Ryan (2004), i.e. that a production scale in the region of 10,000 tonnes per annum would be required. Naturally this assumption could be challenged, but it does seem reasonable. One of the key factors to consider is the nature of the staffing for offshore aquaculture. This model has been predicated on 5,000 tpa ‘farming units’ with just 8 staff assigned to each. It is difficult to contemplate much smaller units, since there would need to be a pro-rata reduction in staff numbers. However, there is always a need for a critical minimum number of staff on any aquaculture project, to allow for holidays, sickness etc. This is probably more important in an offshore situation than it would be inshore.

7.1.1.6 Investor Confidence.
Offshore aquaculture would appear to be a potentially viable way of farming fish, but the scale of operation would need to be significant in order to achieve proper economy of scale. Investment packages in excess of £20 million are indicated for a 10,000 tonne per annum operation. Industrial investors, i.e. existing major aquaculture companies, are unlikely to be persuaded that there is any compelling advantage to moving offshore at this time, but they would at least understand the nature and risks of the investment if they were to be so persuaded. Pure financial investors would probably be very cautious about the risk they would perceive in an industry with which they are not familiar.

7.1.1.7 Potential Market and Impact
The seafood market is complex and there are a large number of references and other sources which should be consulted for detailed analyses. However, the nature of offshore finfish production is likely to contain realistic assessment to consideration of large scale production and as a result, the retail multiple sector as the obvious customer.

There is probably very little prospect of somehow 'bucking the trend' of the current UK markets for seafood products, at least not on any sort of significant scale of production. Any project which is presented for serious investor analysis will require a market proposition which, whilst it could be innovative in its approach, is also founded on an understanding of the reality of what UK consumers are prepared to pay for seafood protein.

This initial overview seems to indicate that for any future high-volume offshore aquaculture in UK waters, and with UK markets in mind, species with a market proposition that can deliver fillets to consumers at around £7 to £8 per kg will need to be considered. If the final end price is much higher, one would anticipate that the product would move into an 'occasional luxury' category for most consumers and that alternative sources of protein which are perceived as being better value would be selected for everyday purchase.

This study indicates that there may be interesting prospects for offshore finfish cultivation (and in relation to market expectations) if considered in a global (rather than UK) context.

This study also suggests that future work on shellfish cultivation in offshore locations might be justified.

7.2 Ecological Considerations

Whilst it is likely that offshore aquaculture production will have less direct environmental impact than is typically attributed to inshore sites (see Benetti et al., 2006), there is little scientific evidence to support some of the acclaimed benefits. The total volume of water exchange may be greater and therefore the dilution factor may be higher for any given pollutant, but this may need to be assessed on a site-by-site, system-by-system basis.

If the biological limitations of the stock dictate that cultivation takes place in conditions which are the same as those that apply inshore, the impacts may indeed be similar. Take for example a situation where, despite a water depth of 80m, the prevailing wave climate and current regime suggests that optimal cultivation would need to take place at a depth of 20 – 30m. In reality, this situation is perhaps not very different from some deeper inshore sites. If one also assumes that farms may need to be of significantly greater scale to offset the additional cost of offshore operations, the notion of less environmental impact may be challenged – particularly, if at such depths the processes of degradation of solid waste material are much slower due to lower temperature and a generally more impoverished benthic community. The use of single point moorings is an option that could be favoured in the open sea where space is less of a limitation. Such mooring systems allow the cage structure(s) to move over a wide arc and therefore result in lower impact per unit area or volume than equivalent production in static cages.

The precautionary principle coupled with the all pervading need to demonstrate "sustainability" would suggest that any plans to set up commercial scale fish farming offshore will, in the initial stages at least, be subject to considerable environmental scrutiny. There will be significant barriers which prospective operators will have to overcome and these should be explicitly acknowledged in attempts to take such developments forward. The assimilative capacity of the offshore environment could be considered greater than inshore, but this assumption will need to be modelled as part of an overall environmental assessment.

Given the proposed scale of some offshore aquaculture ventures, the issue of stock containment and stock security is an important consideration. Our knowledge of the population dynamics and structure of some wild populations of fish species that are being considered for cultivation is far from complete. The escape or release of large numbers of hatchery reared stock would be considered unacceptable and could have a disproportionate impact on some wild stocks where the relative number of wild fish is low – as a result of over fishing for example! Experience of farming in exposed Class 3 sites suggests that maintenance requirements are high and vigilance will be required if net damage and subsequent escapes are to be prevented.

There is anecdotal evidence suggesting that disease incidence is lower in fish farms in exposed conditions and the assumption is that there will be less disease in fish cultivated offshore. However, there is little scientific evidence or practical commercial scale experience in offshore sites to support this assumption. Physical separation from disease agents, particularly parasites which may require intermediate hosts located inshore would be advantageous. But what limited research there is in this area, suggests that wild stocks of fish could provide a reservoir for disease transfer which may be capable affecting offshore sites. It is suggested that "lower" stocking densities may help to reduce the incidence of disease, but this characterisation is simplistic. Many inshore sites now operate at these "lower" stocking densities. If the offshore site or resident fish population is "disease" free, it is also possible that farm stock could be a disease vector.

The proposed siting of offshore aquaculture farms in close proximity to offshore oil and gas platforms, with a view to re-use or co-use of facilities and logistics is, in theory, an attractive proposition. There are, however, a number of potential environmental interactions which may not favour this approach and which would need to be investigated. The potential impact of produced water discharges and drill cuttings for example, will need to be considered.

7.3 Legal Implications

Within the 3nm limit there is an established legal and regulatory framework to permit and control aquaculture activities. This framework is most advanced in Scotland where the majority of marine cage culture takes place and it would seem logical to assume that these rules and regulatory structures could be transposed for use elsewhere in the UK. However, beyond the 3nm limit there are clearly some serious legal and regulatory anomalies that would need to be addressed before aquaculture could take place and for the UK to remain compliant with its obligations under international and EU legislation. In the case of EU legislation, it is possible that the landmark judgement which now requires the UK to observe the Birds and the Habitats Directives out to 200nm could apply to other EU Directives pertinent to aquaculture.

In Scotland, the situation exists, where planning authorities have the capacity to grant permission for a fish farm site out to the 12nm limit, whereas the principal regulator of fish farm discharges; SEPA, has a remit to 3nm only. Beyond the 12nm territorial limit, the legal and regulatory picture becomes even more confused in that the UK has not formally declared an EEZ, but through UNCLOS relies upon the designation of zones to cover specified activities regulated by a competent authority, none of which currently refer to aquaculture *per se*. Whilst some of the established zonal regulations would have some relevance to aquaculture activities, it would seem likely that additional regulation would be required to properly consent and regulate the activities of this industry out to 200nm.

Some existing zonal regulation may also need to be amended to accommodate aquaculture, such as the capacity to attempt recapture of escaped stock. If aquaculture is to expand beyond the limits of the coastal zone, it is important that the option to do so is secured as part of the fundamental legislative revision which is currently under consideration through the UK Marine Bill and the Scottish Marine Strategy.

7.4 Technical, Biological and Logistical Considerations

Typically, marine cage farming sites in Scotland are in sea lochs in relatively unexposed (Class 1 and 2) locations. The technology and expertise to conduct cage culture aquaculture in an economically viable context already exists in relatively near shore environments with significant wave heights of up to 1.0 – 2.0 meters (Norwegian site Class 3). With respect to the stock, the biologically limiting factor in such cases is normally current speed. Much like in Ireland (see Ryan, 2004), existing cage technology and husbandry techniques have been adapted for operations in more marginal exposed sites (Class 3), but this tends to incur greater costs. At present, there is no aquaculture production occurring in UK waters in high or extreme exposure environments (Class 4 or 5). Elsewhere, offshore cage culture is of relatively limited scale and largely experimental.

Such exposed environments remain challenging and are unexploited in the UK because economically more favourable sites in sheltered near shore situations have been sufficient, particularly in Scotland. The fact that more exposed sites in the rest of the UK have not been utilised for finfish cage aquaculture is testimony to the fact that finfish production is a global market and international production capacity has been sufficient to mute the commercial impetus to explore more challenging and less economically attractive sites.

The wave climate that exists in the UK offshore environment, coupled to prevailing weather conditions strongly suggests that finfish aquaculture will need to be conducted in cages or enclosures capable of being submerged for up to several tens of metres for periods of several days and possibly for prolonged periods at lesser depths.

Whilst there is some potential to further adapt existing cage systems it is widely accepted that novel technologies are required to successfully prosecute aquaculture in most open ocean situations. Most of the technological advances in developing aquaculture systems for use in these more exposed categories have taken place in countries where there are limited opportunities to exploit less exposed sites with existing technology.

Over the past twenty years, a range of cage structures have been piloted and still more have been promoted in concept only. Many of the cage structures tested have failed to progress beyond this stage as a result of high cost, structural failure and simply being unfit for the purpose of on-growing fish. Few cage systems have been developed with a fully integrated vision of how they will function as part of a wider production strategy to produce fish at the right price, volume and quality to meet the needs of the consumer.

There is a need to focus effort on the development of remote systems for monitoring every aspect of production at sea. In addition, reliable means of remotely conducting routine maintenance and husbandry tasks are required. Much of this technology and expertise could be developed in existing fish farms situations. Some companies already produce integrated production control and process management solutions for feeding, monitoring of stock and water quality, based on available sensor technology. However, there is considerably more work required to develop systems capable of providing the functionality necessary for offshore operations.

At present, there do not appear to be any “offshore” cages in use in the UK. Of the designs that are either available or in pilot scale trials, the Farmocean and OceanGlobe cage systems would seem to be the most practical for offshore conditions. The OceanGlobe, if successful in trials and of reasonable capital cost, appears to be the most “holistic” design produced thus far. Neither of these systems is designed to function in the offshore conditions which characterise the vast majority of UK waters beyond territorial limits. Some of the more extensive enclosures which rely upon tension to maintain net volume are appealing in concept, but present significant practical challenges in terms of husbandry and maintenance. The designers of these systems may point towards new and emerging technology as the solution to these issues, but in reality the utility of what is proposed has not been properly considered or tested – even in controlled conditions or more benign inshore waters. Sensibly, one would like to see this supporting, but operationally fundamental, technology developed at a practical level before moving on to test cage and enclosure designs that will require their use – if they are to succeed.

The biological scope of the fish may prove to be a significant limitation on offshore cultivation. The conditions within the cage must be conducive to optimise the growth performance of the fish and there appears to be little information on the optimal depth, current speed, light regime etc., that would be applicable to cultivating fish in offshore conditions. Current speeds outside the cage which exceed $1ms^{-1}$ are, for example, not generally recommended. Photoperiod control may be required to minimise maturation, whilst maintaining optimal growth and feeding opportunities. Some broad and scientifically unsubstantiated assumptions have been made about the reduced risk of disease offshore. Work is required to assess the validity of this assumption. Anadromous fish requiring to take-in air to equalise their swim bladders will need special provision if they are to be cultivated in submerged cages.

Almost every aspect of offshore husbandry and maintenance will need to be systematically considered and tested practically. Simply building a pilot scale cage system and then using it as a platform to test other necessary innovations required for its successful deployment offshore would be a costly and outdated way to proceed. Much of the innovation required could be developed and, to a large extent, tested in existing cage structures. Critical to every stage of this process will be the need to refer to viability and cost implications.

The UK has considerable expertise and the development of offshore installations for the oil and gas sectors which operate in some of the worlds most hostile sea conditions. To date, there appears to have been little engagement of this sector in exploring the potential for technology transfer and collaborative development of offshore aquaculture development in the UK.

7.5 Options

The notion of developing large scale fish cultivation in the offshore (open ocean) is clearly appealing if framed in the context of virtually unlimited space, less rigorous regulation, significant economies of scale (if achievable), reduced environmental impact and reduced reliance on wild caught fish stocks etc. From a strategic perspective, greater control over the supply and quality of fish available within the UK and for export may also be a valid consideration. However, thus far, commercial interest in offshore cultivation has been confined to countries where conditions dictate that aquaculture can only develop in more exposed locations – most of which are, in reality, Class 3 sites rather than open ocean. Such conditions occur around much of the UK, but despite potential advantages, available evidence suggests the UK aquaculture production sector has had little appetite for developing offshore cage culture.

Worldwide, interest in offshore aquaculture is showing resurgence, fuelled for example, by fears over the predicted FAO fish gap and in the US by recent legislative changes which now permit offshore aquaculture development.

The UK salmon aquaculture industry has matured into a reasonably stable and valuable food production sector with experience similar to that of other intensive high volume animal production sectors such as pigs and poultry. There is reason to believe that, given time and appropriate market conditions that cod (or an equivalent white fish) will be produced in similar fashion, but with the obvious caveat that, unlike Atlantic salmon, there is still a significant wild supply which will have a strong influence on the time horizon for this scenario. In this respect, one might also wish to assess the Pacific salmon story in some parts of North America, where aquaculture has clearly supplanted the wild catching sector. If the UK aquaculture industry is to expand significantly both in terms of production and geography, there will be a requirement to consider more exposed farm sites (Class 3) in the first instance and, if necessary, offshore sites. Logically, this progression would probably involve adapting and exploiting established technology and expertise, rather than the more costly and much higher risk scenario of developing systems capable of truly offshore operation.

The fact that the UK has an established oil and gas sector and an emerging offshore renewables sector, all of which rely upon substantial fixed offshore installations, offers an added dimension to the consideration of offshore aquaculture production. Co-use or possible re-use of these structures could, in principle, offer a shortcut to offshore aquaculture becoming established as a viable means of production. Deferring the cost of decommissioning redundant offshore structures is a potential driver for this process. But, economic and practical aspects of combining aquaculture production with operational oil and gas platforms would seem to preclude this as a viable option. The use of redundant platforms may be possible, but the cost of maintaining structures which are likely to be at the end of their operational and design life, coupled to the ongoing liability for decommissioning suggests that this is an unlikely option – for the UK at least. The growth in offshore renewable energy may provide a genuine opportunity for certain types of aquaculture. Windfarms in less exposed locations clearly have potential for some forms of shellfish culture. Whether such offshore sites are suitable for cage fish cultivation is, in the first instance, dependant upon the depth, together with the prevailing wave climate and current conditions. Most of the current or planned offshore windfarm sites would, at least in cursory analysis, not appear suitable, but more detailed discussion with windfarm developers may be warranted. In the longer term, some types of wave power generators which damp wave energy may offer a more realistic complement to cage based aquaculture operations. In any event, the aquaculture sector should seek to align itself with offshore renewables development with a view to capitalising on potential synergies. These are strategic considerations given the projected timescales for offshore developments, but there is every prospect these timescales may be commuted as the UK's energy supplies decline and our reliance on costly and potentially unreliable imports increases.

Elsewhere in this report we have highlighted the technological deficiencies which have, or are likely, to impede commercial aquaculture even in moving to more exposed locations and ultimately offshore. These conditions will demand high levels of automation and remote unmanned operations. At present, this capacity has not been developed and considerable work will be required to meet such challenges.

There are also biological limitations of the stock which will need careful consideration if viable cultivation is to take place in conditions which preclude established husbandry practices. There is little scientific knowledge of some of the key production and performance criteria that would apply to cultivating stock in cages which may need to be submerged at considerable depth for prolonged periods.

The cost of taking finfish cage aquaculture into the offshore environment will be considerable. This report highlights a wide range of challenges, many of which will require expensive research and development (R&D). The UK's expenditure on R&D in the aquaculture sector is estimated to be in the region of £6 million per annum and this figure is, in real terms, declining. Evidence suggests that over the last decade, only a very small proportion of the available funds have been committed to technology development (see http://www.defra.gov.uk/science/Areas/aquatic/default.htm and http://www.frmltd.com).

If offshore aquaculture is to be considered as a strategically desirable way forward, the UK (both government and industry) would need to allocate additional resources for R&D or refocus current budget priorities. To spread both cost and risk the UK should actively seek to engage with international efforts to develop offshore technology. Specific, well planned and rigorously co-ordinated pilot scale initiatives could also be considered particularly with respect to shellfish cultivation alongside windfarm developments, but experience through the LINK Aquaculture Programme, for example, suggests that these should only be taken forward as collaborative ventures between government, industry and the research community.

If pilot scale projects are to be taken forward, it would seem logical for these to be conducted within the 3nm limit in the first instance because, at present, this is the only area where a proper consenting and regulatory framework exists for aquaculture in UK waters. Many of the biological and technical precursors highlighted in this report, which would be required to underpin the viability of offshore aquaculture could potentially be tested with existing cage systems in appropriate exposed sites. Whilst frustrating for those championing offshore aquaculture cage development, it would be advisable to resolve these critical issues before considering pilot scale deployments of some of the more innovative and ambitious cage concepts that are being promoted. The UK has a history of failure in the development of new species for aquaculture and some aquaculture technologies. This has occurred either because questions over economic and commercial viability were overshadowed by the desire to conduct research or simply gain funding. In some cases such ventures have been funded for purely political reasons and without proper consideration of their long term viability. Much of the UK's finfish aquaculture is in foreign (principally Norwegian) ownership and there is clear evidence that in some instances, successful technology and innovation developed at the expense of the UK tax payer has ultimately been used elsewhere with little or no tangible benefit to the UK economy.

Offshore aquaculture is fundamentally appealing and could be strategically important to the UK in the future. This report has sought to provide a balanced assessment of the prospect for developing this sector in the UK, whilst recognising the practical, legal and economic constraints. From the evidence provided, we would advise careful consideration of properly justified calls for R&D in support of aquaculture development in more exposed locations with a view to better defining the prospects for full offshore operations in the future.

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