Aquaculture

SUBSEA ENGINEERING OPPORTUNITY
International Market Insights Report Series

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Scottish Enterprise

Contents

1. Introduction

This report is part of a series of reports considering the opportunities for the Scottish oil and gas (O&G) subsea supply chain in other subsea and related markets. The report is a desk review considering the international activity of each of the sectors including where there is current activity and where there is the potential for activity based on published targets and available resource and opportunity. The report also considers the particular synergies of the given sector and the subsea oil and gas supply chain. These opportunities cover where there is a direct cross over and also where there are opportunities for collaboration to provide innovative solutions.

Aquaculture is the global activity of farming fish, crustaceans and aquatic plants, worth almost £125bn globally in 2015. Aquaculture is practiced in freshwater as well as the marine environment, the latter known as mariculture, is the area this report will focus on.

Mariculture is an intensive activity in terms of inputs such as energy and feed. It is therefore dominated by high value species such as salmon, sea bass, sea bream, mussels and oysters. Table 1 below shows the countries with significant mariculture output. These are described in greater detail in Section 4. The main salmon producing countries are Norway, Chile, Scotland and Canada

Table 1: Countries with mariculture production showing total value of the industry as well as value of main mariculture species. Source: various

Country	**Main species farmed**	**Value of industry** Volume/value	**Main mariculture species value** Volume / value	**Target** (where available)
Australia	Rock lobster, salmonids, tuna	Total production: 89 217 tonnes / £674m	Salmonids: 66,020 tonnes /£359m	
Canada	Atlantic salmon, trout	Total production: 200,565 tonnes / £811m	Salmon: 140,396 tonnes / £681	
Chile	Atlantic salmon	Total production: 800,000 tonnes / £3.2bn	Salmon: 800,000 tonnes / £3.2bn	
Egypt	Tilapia, Flat head grey mullet, European seabass and gilthead sea bream	Total production: 1,230,000 tonnes	Flathead grey mullet: 129,000 tonnes	Additional 200,000 tonnes of marine fish
France	Mussels and oysters; salmon, trout, seabass and seabream	Total production: 205,000 tonnes / £634m	Trout and Salmon: 35,650 tonnes / £105m Seabream, seabass: 5150 tonnes / £31m	233% increase in marine fish by 2020 increase total production value £896m
Greece	European seabass, gilthead seabream	Total production: 145,373 tonnes / £557m	Seabass and seabream: 90,889 tonnes	170,000 tonnes in 2020 from
Iceland	Atlantic salmon, Artic Char	Total production: 11,605 tonnes	Salmon: 5205 tonnes	

Japan	Aquatic plants, shellfish, amberjack, seabream	Total production: 1,105,000 tonnes / £3.3bn	Yellowtail and greater amberjack: 145,000 tonnes Red seabream: 67,500 tonnes	Ambitions to move offshore
Norway	Atlantic salmon	Total production: 1,326,156 tonnes / £5.8bn	Salmon: 1,233,619 tonnes	Potentially worth £10.8bn by 2030
Russia	Carp, Atlantic salmon, rainbow trout	Total production: 160,000 tonnes	Salmon: 20,000 tonnes	700,000 tonnes by 2030
Spain	Mussels, gilthead seabream and European seabass	Total production: 285,000 tonnes / £415m	Seabass and seabream: 34,075 tonnes	£481m by 2020 £680m by 2030 32% increase in marine finfish
Turkey	European seabass, gilthead seabream and trout	Total production: 240,334 tonnes £616m	European seabass 75,164 tonnes Gilthead seabream: 51,844 tonnes	Predicting 500,000 tonnes by 2023
United Kingdom	Atlantic salmon and trout	Total production: 171,035 tonnes	Salmon: 162,817 tonnes / £766m	350,000 tonnes by 2030

The aquaculture industry is technically advanced, embracing developments in automation, video surveillance and sensors. Such solutions include methods for measuring when fish are sated; identification and removal of parasites; and automated feeding systems. The industry faces a challenge to overcome factors such as coastal constraints, waste management and sea lice. Technology innovation can be a solution to these and other challenges, factoring in animal welfare considerations, but they also require a willingness to adopt the changes at both a company and regulatory level.

Such technology could include closed or semi-closed systems as well as the expansion of farms to locations further offshore. Offshore sites will be in higher energy environments and therefore the technology for the cages will need to be developed and expanded to ensure that they are fit for purpose in this new environment. The increased cost of the technology and offshore operating costs would need to be offset by a significant increase in production from these sites. This also provides an opportunity for the subsea oil and gas supply chain who have experience and technology solutions for these higher energy environments, such as mooring lines; anchors; inspection, repair and maintenance; remote monitoring; HSE and offshore logistics amongst others.

2. Sector Overview

Aquaculture is the practice of farming aquatic organisms in offshore, coastal and inland waters and fishing encompasses the harvesting of wild stocks of aquatic organisms. This report will focus specifically on aquaculture as it has a more significant technology crossover with subsea engineering. A subset of aquaculture is *mariculture* which specifically refers to the controlled production of aquatic organisms in the marine environment or in ponds, dams or raceways filled with seawater. Of the disciplines of aquaculture, mariculture has the biggest technology synergies with subsea oil and gas engineering.

As well as fish such as finfish, crustaceans, molluscs, etc. aquaculture also includes the growth sector of aquatic plants. Mostly seaweeds, aquatic plants accounted for 29.4 million tonnes of aquaculture production in 2015, representing 96 percent of total aquatic plant harvest (i.e. 4% from wild harvest). Aquatic plants are used in the food industry as well as in the production of biofuels, cosmetics, animal feed, fertilisers and nutraceuticals (amongst others).

Aquaculture has seen rapid growth with an increase from 3 million tonnes in the 1970s to almost 77 million tonnes in 2015.[1] The UN FAO and the World Bank estimate that aquaculture will provide almost two-thirds of global food fish consumption by 2030, Figure 1. This upsurge is due to an increase in demand and a levelling off from wild capture fish production, showing aquaculture's real importance for global food security. Over the last ten years aquaculture has grown at an average annual rate of 6.6 percent, although the growth rate is slowing, the upward trend is expected to continue.[2] Demand for fish is increasing as the global population increases and with it demand for protein. Changes in food habits, such as rising incomes and moves to more westernised diets are also accelerating the increasing demand for protein globally.[3] Aquatic products can help to supply this additional protein requirement with the added benefit of a lower carbon footprint, and better feed conversion ratio than traditional livestock.[4,5] In addition to this, aquaculture can reduce the pressure on land for food production, which will increase as the population grows. Currently only 5% of food production takes place in the sea, there is therefore an opportunity to increase marine food production in a sustainable manner.[6] The Table 2 and Table 3 below show the value and type of the global 2015 aquaculture production:

Table 2: World aquaculture production in 2015 Adapted from. FAN #56

Product	Quantity (live weight) *million tonnes*	Value (first sale) *US$ billion*
Food Fish*	76.6	157.9 (£121.1bn)
Aquatic Plants**	29.4	4.8 (£3.7bn)
Non-food products	0.041	0.208 (£159mn)
Total	**106**	**162.9 (£124.9bn)**

[1] Food and Agriculture Organisation of the United Nations (UN FAO), Fisheries and Aquaculture Statistics 2015, Yearbook, 2017.
[2] UNFAO, FAO Aquaculture Newsletter (FAN), No 56, 2017
[3] Henchion, M., Hayes, M., Mullen, A. M., Fenelon, M. and Tiwari, B., Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium, *Foods*, **6**, 2017 p53
[4] IBISWorld, Aquaculture - UK Market Research Report, 2017
[5] Highlands and Islands Enterprise, Value of Scottish Aquaculture, 2017
[6] Aquaculture in Norway, Norwegian Seafood Council, 2011.

* Food fish includes finfish crustaceans, molluscs and other aquatic animals such as sea urchins and sea cucumbers, frogs and aquatic turtles, etc. farmed crocodiles and alligators are excluded
** Aquatic plants include mostly seaweeds, plus some microalgae

Table 3: Main cultured species of world food fish aquaculture production in 2015. FAO yearbook

Type of product	Weight	Percent
Finfish	51.9 million tonnes	68 %
Molluscs	16.4 million tonnes	21 %
Crustaceans	7.4 million tonnes	10 %
Other aquatic animal species	0.9 million tonnes	1 %

Inland finfish farming accounted for 59 percent (43.6 million tonnes) of world aquaculture production in 2015, making it by far the largest single part of aquaculture.[1] Inland farming is dominated by the farming of carp in China, see Figure 5, in ponds and reservoirs, as well as drainage canals and paddy fields. There is an integration in the inland aquaculture sector where the waste from fish production is used to fertilise fields and the crops grown on these fertilized fields are used to feed the cultivated fish. Inland farming is carried out in shallow water, from as little as 5 – 10 cm in paddy fields to 2-3 m in ponds and reservoirs – shallow bays are sectioned of with netting or screens to accommodate the fish. As this is the case, this will not be the focus of the study as there will be limited cross-over with subsea technologies. [7]

Aquaculture historically is an industry that is largely self contained with aquaculture companies covering many or most aspects of the supply chain. Technology is largely developed from the balance sheet, there is therefore an opportunity to help access funding opportunities, such as the European Marine Fisheries Fund or Blue Growth under Horizon 2020.

2.1. Growth Trends

In terms of food fish production (rather than overall production as Figure 1 shows) aquaculture is expected to contribute 62% to the total by 2030. As part of this expected growth there is a need for innovation and improved efficiencies in current aquaculture practices to allow for this growth. Currently growth is limited by barriers such as environmental concerns around concentrations of nutrients, waste and pathogen treatment residues (such as sealice treatments); scale of projects in sheltered coastal waters and availability of sites in these sheltered locations. Some of these can be overcome through innovative techniques such as closed, or semi-closed, loop systems to manage the waste and contaminated water outputs from the farms, and also through expansion further offshore to make use of greater space and volumes. These techniques, although a long-term strategy, could provide opportunities for the subsea oil and gas engineering sector to share technology solutions, knowledge and expertise as well as prospects for innovation.

[7] UNFAO, Freshwater Fisheries and Aquaculture in China, FAO Fisheries Technical Paper No. 168, 1976

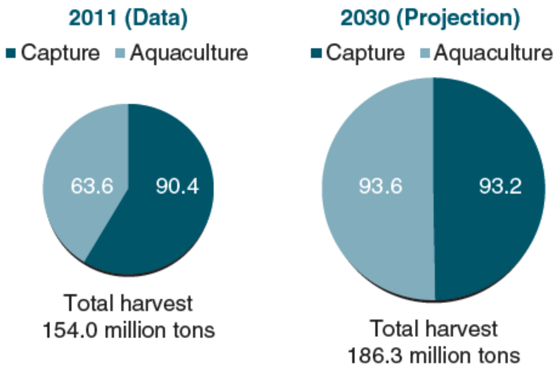

Figure 1: Charts showing the split between capture and aquaculture production for 2011 and 2030. Source: World Bank

Figure 1 and Figure 2 show the overall predicted share change between wild capture and aquaculture from 2011 to 2030.[8]

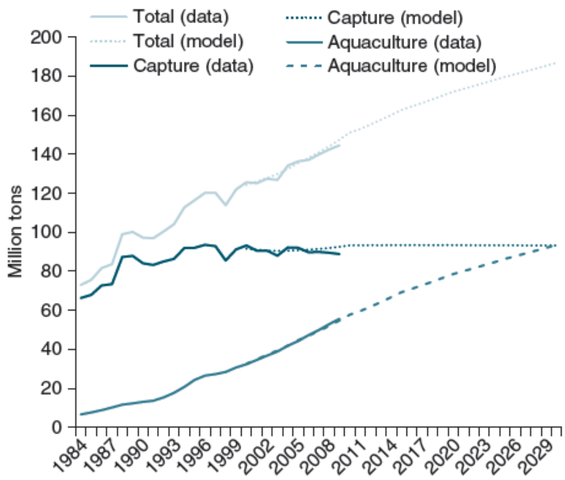

Figure 2: Graph showing data and modelled data for production up to 2030. Source: The World Bank

The trend that the World Bank's model predicts for capture and aquaculture is shown in Figure 2. There is a steady growth of production from aquaculture, albeit that the growth rate slows marginally in the second half of the 2020s, and a levelling of capture, at slightly higher than current levels. The figures also show that the total volume produced increases by over 20% from 2011 to 2030. Whilst aquaculture growth peaked in the 1980s with an annual growth rate of 10.8%, growth rates have declined since then (9.5% in 1990s and 5.1% from 2001 – 2015)[1] but as the figures show growth will continue to 2030. Beyond 2030 the World Bank believes that aquaculture will continue to grow and become the dominant source of fish.[8] It should be noted that the World Bank model concentrates on fish (finfish, crustaceans, molluscs, etc.) and not aquatic food, it is therefore the 77 million tonne figure from Table 2 that should be compared to Figure 1 & Figure 2, not the total aquaculture figure of 106 million tonnes.

[8] World Bank. 2013. *Fish to 2030: prospects for fisheries and aquaculture (English)*. Agriculture and environmental services discussion paper; no. 3. Washington DC; World Bank Group.

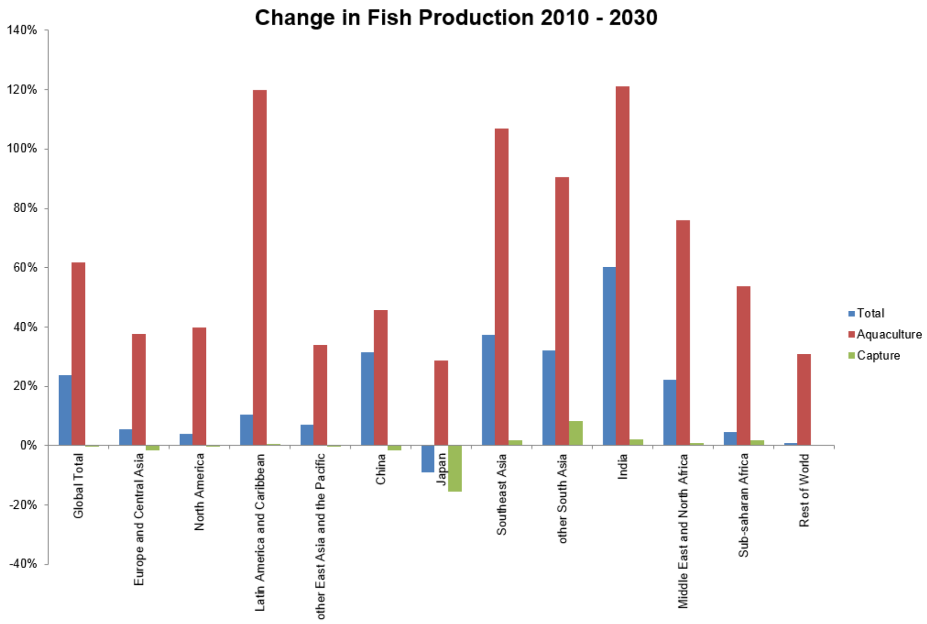

Figure 3: Historic and predicted changes in fish production from 2010 - 2030. Source: World Bank

Figure 3 highlights the significant predicted increase in share of aquaculture production particularly in Latin America and the Caribbean (119%) and regions in Asia (average 71.2%). The chart also highlights the very small increases or decrease in capture as a means of fish production. Further detail on specific countries can be found in Section 4.

2.2. Utilization

As can be seen from Figure 4, production of fish is predominantly for human consumption. Approximately 45% of the 149 million tonnes produced (both fisheries and aquaculture) for food fish is sold in a live and fresh form.

Global per capita consumption of fish was estimated at 19.8 kg in 2013 and looks to have risen to 20.3 kg in 2015. Fish accounts for approximately 17% of world's animal protein intake and 6.7% of overall protein. Fish provides a high-value protein rich in a wide range of essential micronutrients, including various vitamins, minerals, and polyunsaturated omega-3 fatty acids as well as being low in saturated fats, carbohydrates and cholesterol. It therefore plays an important role in food and national security in feeding vulnerable populations around the globe.[1,8]

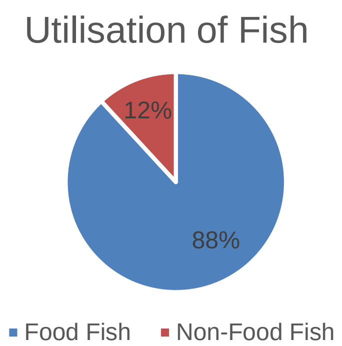

Figure 4: Utilisation of aquaculture production in 2015, non-food uses include fishmeal and fish oil. Source FAO yearbook

Non-food fish is largely used in the production of fishmeal and fish oil. Fishmeal and fish oil are used for the feeding of aquaculture products, poultry and swine, with the percentage of produced fishmeal and fish oil used in aquaculture production growing from the 1980s to 2006.[9] Fishmeal and fish oil accounts for up to 20% of feed in Scottish reared Atlantic salmon (levels varying by species and countries) with the remainder being made up from soya and cereals.

In terms of aquatic plants, which make up 28% by weight and 3% by value of aquaculture production (in 2015), the recent increase in interest has been driven by a desire to use seaweeds and other algae for the generation of biofuels. The main uses of aquatic plants are food (or "sea vegetables") or condiments and cosmetics. They can also be used for animal feed, including supplements, chemicals (e.g. hydrocolloids), fertilizers and nutraceuticals (e.g. nutrients and dietary supplements for human consumption) and at development stage there are options to use them for bioremediation or biofuel production (via anaerobic digestion).[10]

2.3. Trade

Globally, around 35% of fish production (live weight equivalent) was exported in 2015, with a value of US$133 billion (£93.7bn). This value is down 10% from 2014, largely due to the strength of the US Dollar against multiple other major seafood exporting countries currencies as well as the weakening of some key emerging markets and a lower price for several important species.[1]

Table 4 below highlights the main trends in the global import and export of aquaculture products.

Table 4: Details on the world import and export of aquaculture and fisheries production. Source FAO Yearbook

World Imports	- Developed countries account for approximately 71% of fisheries imports - The European Union is the largest market, representing 37% of the world market. If interregional trade is removed this drops to 22%, however this is still the largest market. - The USA and Japan jointly account for 26% of the world import market.
World Exports	- China is the main exporting country by a significant margin - Norway, Vietnam and the USA follow. - Developing countries play a significant role in export with 54% of the total by value [57% by quantity (live weight equivalent)].

In developing countries, the net export of fish food (i.e. total value of exports, less total value of imports) has been steadily increasing from US$18bn in 1995 to US$22bn in 2005 and US$35bn in 2015. In addition to this growth it is worth noting that these figures are significantly higher than the figures for other agricultural commodities such as rice, coffee and tea.[1]

[9] UNFAO, FAO Fisheries and Aquaculture Technical Paper 518, Fish as Feed Inputs for Aquaculture, 2009
[10] Capuzzo, E. and McKie, T., Seaweed in the UK and abroad – status, products, limitations, gaps and Cefas role, 2016

2.4. Main Cultured Species

Figure 5 shows the total aquaculture production of food fish for 2015 by value in USD, the total value of which is US$157.9bn (£121.1bn). The top 30 species for aquaculture account for 66% of production at a value of US$104.6bn (£77.8bn).

Members of the Carp family (e.g. common carp, bighead carp, major carp) are the biggest contributors to the total making up 20% of the total at a value of US$31.6bn (£23.5bn), however these are farmed inland. Of particular interest to subsea are the seawater species, those produced through mariculture, the biggest of which is whiteleg shrimp, also know as the white pacific shrimp, (US$18.9bn, 13%) followed by Atlantic salmon (US$11.9bn, 8%) and Chinese mitten crab (US$5.7bn, 4%).

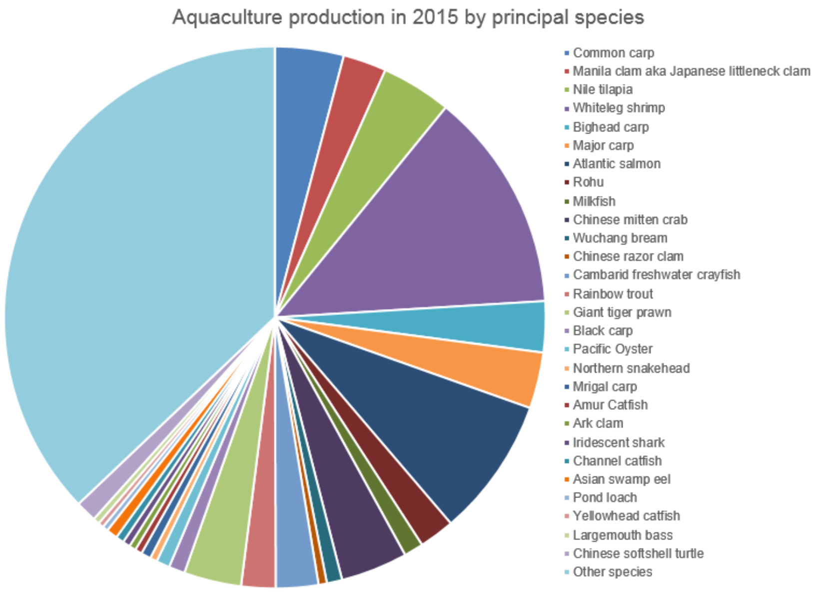

Figure 5: Aquaculture production in 2015. Source: FAO yearbook 2015

Salmon and trout are the two most important export species, by value, accounting for 17 percent of total value of internationally traded fish products. The other main groups of exported species are shrimps and prawns (at 16%), groundfish e.g. hake, cod, haddock (10%), tuna (9%), fishmeal (3%) and fish oil (1%).[1]

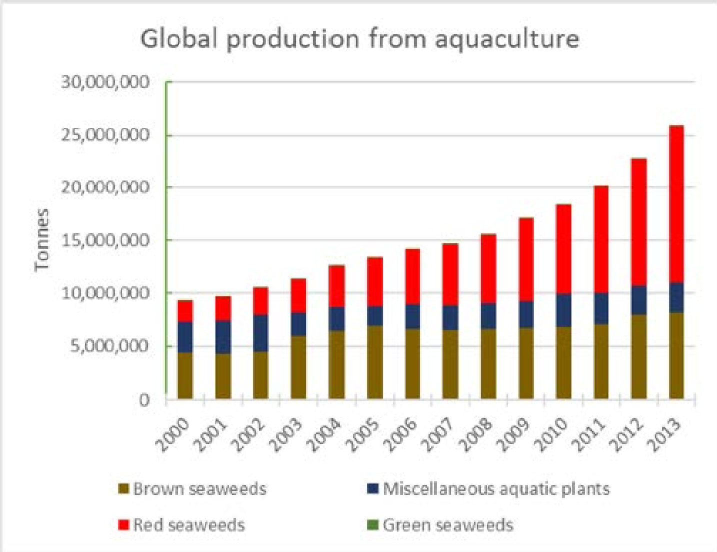

Figure 6: Global cumulative annual aquatic plant production from aquaculture showing the main types of aquatic plants farmed. source: Cefas

Red and brown seaweeds constitute over 97% of globally produced marine plants, as shown in Figure 6. From evidence presented by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) both red and brown seaweeds increased during the study period (2010 – 2014) by 84 percent for red seaweeds, *Euchema*, and 47% for brown seaweeds, *Japanese Kelp*. Green seaweeds have decreased by 30 percent and miscellaneous marine plants by 79 percent over the same period. For wild harvest, brown seaweeds dominate, and there is a greater percentage of miscellaneous marine plants.[10]

Globally different seaweeds are prominent in different locations from both wild harvest and aquaculture. Europe is dominated by brown seaweeds, whereas Africa produces mostly red seaweeds. America produces both, with a slight dominance of red seaweed. Asia also produces both and has the highest proportion of miscellaneous marine plants. Oceania produces both with the dominance changing from brown to red seaweed in 2006/2007. This change is assumed to be due to a change from wild harvest of brown seaweed to aquaculture of red seaweeds in 2007.[10]

2.5. Sustainability of Aquaculture

As with all growing sectors there must be an emphasis on sustainability, and aquaculture is no exception. Consideration should be given to:

- *Other water users* – marine spatial planning is an important tool to be used by regional and national governments, the aquaculture sector can engage with this process to promote their requirements. Marine spatial planning is used widely but will be in different stages across regions and countries.
- *Use of medicines and treatments* – fish health is a hugely important aspect to aquaculture, although no longer using the same amount of antibiotics as they were previously perceived to, there is still health concerns, such as sea lice treatment that needs to be used.
- *Feed* (use of fish) – there is a negative perception about the use of fish to feed farmed fish, however the fish used for feed is not fish that would be used for human consumption. 1 kg farmed salmon requires 1.15 kg of feed (from 2-2.5 kg of wild fish) Wild salmon require 10 kg of feed to grow 1 kg.[6]
- *Energy use and efficiency* – use of energy for feeding systems, communications and control systems largely comes from diesel generators, the impact of this should be considered and

the opportunity for renewable energy solutions to be implemented. Aquaculture farms are energy intensive.

- *Emissions and discharges* – fish produce faecal matter, this in addition to non-assimilated feed that is lost to the water course, which can cause eutrophication of the local environment if it is not managed. Initially an assurance of a sufficient flow of water to ensure dispersal of this organic matter is required, research is also being conducted into the use of closed or semi-closed systems.
- *Impact on biodiversity* – as well as the organic waste and associated risk of eutrophication, aquaculture farms must ensure that there are no escapes of farmed salmon from the farm as escapees pose a risk to native salmon species.

All these aspects have an impact on the design of the aquaculture farm, including cages, sensors, etc. these will therefore be considered again in Section 3 – Subsea Engineering Needs.

2.6. Aquaculture Challenges

In the UK and further afield the aquaculture industry faces challenges that are limiting its expansion. Technical solutions can overcome these challenges, but they require innovation and a willingness to adopt the changes at both a company and regulatory level (licensing, etc.).

One challenge is space. The size of fish farms is limited by the consenting rules due to animal welfare, the amount of treatment for e.g. sea lice that is required as well as the amount of waste produced by the salmon and its affect on the local environment. A further aspect of this is access to areas for the development of new or expanded farms due to the pressure of other coastal users such as energy generation, transport, sewage outflows, fishing (wild capture) and tourism.

This can be overcome through technological advances in terms of improving the density of salmon in existing cages through the better delivery of treatments and management of waste disposal and ensuring a good throughflow of water to ensure dispersal of unassimilated feed and waste matter, coupled with further research into the potential deployment of closed or semi-closed systems. Another potential solution is the relocation of farms from sheltered inshore locations to sites further offshore. These sites will be in higher energy environments and therefore the technology for the cages will need to be developed and expanded to ensure that they are fit for purpose in this new environment. The increased cost of the technology and offshore operating costs would need to be offset by a significant increase in production from these sites. The technology development requirement is discussed further in Section 3.

It is likely that technology development in aquaculture will be led in areas that are farming species that reach a premium price point such as Atlantic salmon. As the gains through lower mortality rates, higher density allowances within cages and reduced interventions will be more readily seen. It is likely though that any technological advancements will subsequently be passed through the aquaculture sector.

3. Subsea Engineering Needs

The different strands of aquaculture have different engineering needs. This report will concentrate on the mariculture aspects as these have the greatest crossovers with subsea engineering and are described below. Inland farming aquaculture is generally carried out in shallow waters and so although there will likely be benefits from technology development, particularly in disease control and feed conversion that can cross over from mariculture these areas are less relevant and have less immediacy to the oil and gas subsea supply chain.

3.1. Mariculture of finfish

The lifecycle of finfish in mariculture is described in the figure below which shows the production of fish fry in hatcheries, often in semi-closed and closed recirculating systems to improve efficiency and quality. This is followed by their transfer, once they reach an appropriate size (~ 100+ g) into the marine environment, the hatchery process is typically 6 months. Once in the sea, the fish are housed in cages consisting of a steel or high-density polyethylene (HDPE) plastic from which a net is hung forming the enclosure. The nets are made from textiles or plastics and require regular maintenance, there has been some interest in Chile to make the nets from metal as they require less maintenance, but have a higher capex. Often there are nets over the surface as well to protect the fish from predators. The cages are often deployed in groups (generally between 6 and 10 cages in Europe, larger groups in Chile) with feed coming from a central feeding barge or onshore and feed into each cage through pipes. The farms are generally placed in sheltered or semi-exposed areas such as fjords and bays, to protect the farms from the worst of the weather. The marine section of the lifecycle is typically 18 months (now nearer 16 months on many sites), meaning an overall 2-year lifecycle, improvements in feed conversion rates can reduce the time at sea.[11, 12]

The size of fish farms varies by country based on space available and local regulations in terms of fish density, some examples are below:

- In Scotland, cages are generally 80-100m diameter and consented for 2,500 tonnes of fish[13]
- In Norway, cages are in the range 50 – 200 m diameter, the nets are between 20 to 50 m deep. A cage would be consented to 3-4,000 tonnes of fish.[6]
- In Greece, stock densities are approximately 10-15 kg of fish per cubic metre, they have a feed conversion ratio of around 1.6.[11]
- In Europe, cage fish farms usually occupy between 1 and 5 hectares per installation.[14]

Marine finfish farms are serviced by boat and most now employ automated feeding systems which are supplied from barges moored close to the farm site. At larger sites, such as in Norway, these can also include accommodation for offshore workers. Activities also include counting, classifications by

[11] UNFAO, National Aquaculture Sector Overview, Greece, 2005
[12] Suplicy, F. and Wurmann, C., KTP Marine Market Brazil, Chile and Peru: A general overview and Investments opportunities, 2016
[13] Scottish Aquaculture Innovation Centre
[14] Dempster, T., and Sanchez-Jerez, P., Aquaculture and Coastal Space Management in Europe: An Ecological Perspective, Aquaculture in the Ecosystem (book), 2014

size, vaccinations and other treatments, removal of mortalities, etc. For harvesting, fish are either gathered and transported live in specialised vessels or are partially processed and transported on ice at the farm site. Live transport results in a better quality final product and is being an increasingly used technique.

Managed grow-out sites for organisms reared from fry, spat and juveniles include production facilities such as:
- Ponds
- Tanks
- Raceways
- Cages
- Pens
- Barrages
- Integrated vallicoltura production (lagoon fish breeding)
- Private, tidal ponds (tambaks)
- Poles, ropes and net bags for molluscs
- Aquatic plants from planted or suspended facilities[1]

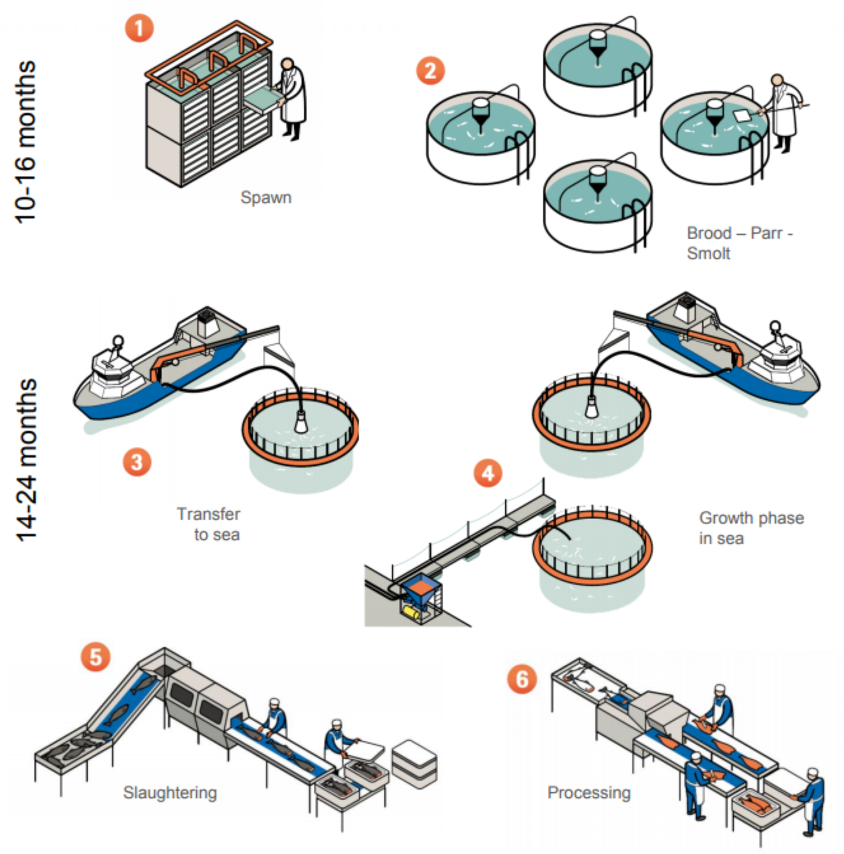

Figure 7: Illustration of the production process of salmon. Source: Marine Harvest

The main areas of technology from the aquaculture sector that cross with the oil and gas subsea supply chain include:

- Materials for subsea use – e.g. those for cages and nets
- Subsea maintenance of nets and cages
- Floating production unit crossover with the feed supply barges
- Moorings and foundations for the farms
- For large farms, offshore accommodation
- Marine vessel logistics
- Site surveys for EIAs
- Sensors for water quality including temperature, but also organic matter
- Pumps – movement of live fish e.g. from hatcheries to the ocean, for sizing and also during harvesting
- Hydraulics for the automated supply of feed and treatment to the fish cages

3.2. Mariculture of molluscs and crustaceans

Molluscs, such as mussels and oysters, are grown on ropes that are suspended in the water column. The seed is collected in the wild by hanging nets in special sites for a period to gather the seed. The molluscs are then either grown on in-situ or transported to another area for the growing phase. The mussels grow on ropes suspended from a surface rope or barge that is kept afloat. These surface ropes are often in excess of 100m in length. The vertical ropes hang at intervals, decided by the farmers, and will be based on balancing maximum production with the availability of nutrition for the mussels to grow. Too close together means that less nutrition is available and leads to longer growing times. In some cases, farmers may strip the ropes to classify the mussels by size before re-establishing them on the ropes grouped by size. This means they should reach harvesting size together. The ropes are kept separate by weighted anchors, mostly concrete based, weighing 10 tonnes. These farm servicing activities take place on floating barges equipped with all the necessary equipment including cranes and means for size classification. The growing time of mussels is approximately 12 – 18 months. Farming of molluscs and crustaceans occupies much greater space than finfish farming, with growing areas of 3-4,000 ha.[12,14] Production of molluscs and crustaceans is less technically advanced than finfish farming, with more seasonal aspects to the work. The main area of crossover with the O&G supply chain would be mooring lines and floats. However, as there is not an appetite for moving mollusc and crustacean operations further offshore this is not a significant opportunity for diversification.

3.3. Mariculture of aquatic plants

Seaweeds are grown in two ways depending on the type:

- Vegetative cultivation is widely used where seaweeds can be grown from other piece of the seaweed. This is common in the seaweeds grown for hydrocolloid uses e.g. agar. Pieces of the seaweed are cultivated attached to ropes suspended in the water column or on the seabed, they can be harvested to remove the whole plant once a suitable size and reseeded with pieces cut from the harvested seaweed. Or harvested in such a way that some of the plant is left, and can regrow. Management of this method involves ensuring appropriate conditions such as light, salinity, nutrient availability and temperature.
- Reproductive cycle cultivation is used for many of the edible seaweeds such as the

Laminaria's. the seaweed has two distinct reproductive phases, at the sporophyte phase, which is also the phase for harvesting, the mature sporophyte releases spores that germinate and become microscopic gametophytes. This is the next reproductive phase, here the gametophytes become fertile and release sperm and eggs that join to form embryonic sporophytes, which then grow to reproduce and be harvested.[15]

The large-scale aquaculture production of seaweeds and other aquatic plants is still relatively young, with the majority of collection still occurring through wild harvest (and possibly even more so than reported as it is likely that there is unreported collection from washed up seaweed collected from beaches). One of the challenges that remains here is the scaling up of the business as an aquaculture business, particularly as it is a labour-intensive process. Successfully, both environmentally and economically, scaling the aquaculture of seaweeds and aquatic plants will have knock-on effect for increased use of these products such as biofuels. Other challenges also prevail, such as clearer marine licensing procedures, as often current regulations are based around shell and finfish farming.[10]

Crossover with the oil and gas subsea sector includes:
- Moorings lines and floating barges
- Surveys for EIA

3.4. Technology

The Scottish Salmon Producers Association state that salmon producers invested over £53m in capital equipment in 2014.[4]

A sample of equipment requirements for aquaculture include[16,17]:
- Fish holding tanks
- Cages, nets and net gear
- Pontoons
- Feeding systems
- Vessels – fish transportation
- Screen, biological, and fine solids filters
- Aerators
- Pumps/Screws (vacuum/lifting devices for fish loading and transport)
- Underwater cameras and lights
- Autonomous Underwater Vehicles / marine robots
- Bridge systems
- Echo sounders
- Sonars
- Subsea monitoring
- Ballast and service tank gauging
- Dissolved gas sensors / wet chemical analyzers
- Fleet Management Software
- Sensors and Transmitters

[15] UNFAO, A guide to the seaweed industry, FAO Fisheries Technical Paper 441, 2003
[16] Subsea UK, Subsea Technology and Engineering, 2014
[17] Kongsberg website, Products by Industry, Aquaculture, accessed January 2018.

- Tank gauging and measurement systems
- Information and safety systems
- Data transfer

3.5. Aquaculture Challenges

EY, in their Norwegian Aquaculture Analysis, comment that although improvements through technological solutions are currently fragmented, the need for these solutions will stimulate R&D. They have seen new players entering the aquaculture market from across offshore sectors, such as subsea, marine, shipping and equipment companies.[18] The increased focus on R&D through finding solutions to the challenges detailed below, provide an opportunity for the aquaculture industry, but also many offshore related industries, including subsea engineering, that can share their expertise and knowledge and develop themselves in the process.

The key challenges in the development of aquaculture that have the potential for subsea engineering supply chain crossover are described below:

- *Further offshore / High energy sites*

The movement of aquaculture operations further offshore, out of the sheltered bay and fjords, they currently inhabit is seen as a potential solution for biological issues as well as reducing the competition for space in the coastal environments. Offshore sites have the potential to allow larger farms with much increased production limits and smaller impacts on the local environment. This move poses its own challenges as the sites further offshore are exposed to the ocean conditions. This means that the equipment used in the sites needs to be more heavily engineered in order to withstand this higher energy environment. It is here lessons from the O&G subsea engineering supply chain can facilitate this move through knowledge of foundations and anchors; mooring lines; structure design and materials.
A move further offshore will increase capex and opex, but the opportunity to produce larger volumes will counter this. As well as the technology aspect for mariculture offshore there is also a need to consider in parallel the offshore logistics; security measures and the regulatory framework required to facilitate the move offshore. A 2008 study by Dempster postulated that it would be 10-20 years before a major portion of mariculture moved offshore. This prediction is reasonable as at 10 years on from this we are seeing the first movers in this. The main drive in this is coming from Norway, who deployed their first offshore fish farm in 2017.[5,14,12]

Ocean Farm 1, from SalMar seen in the figure below, is the first full-scale pilot offshore mariculture facility. It is set to test both the biological and technological aspects of farming fish offshore.[19]

[18] EY, The Norwegian Aquaculture Analysis 2016
[19] SalMar website, Offshore Fish Farming, A new era in fish farming is on its way, accessed January 2018

Figure 8: Ocean Farm 1, SalMar's full scale pilot offshore fish farm. Source: SalMar

- *Anchors & Moorings*

Anchors and moorings are an important technological aspect of current fish farms as well as a critical component for a potential move into higher energy environment. Subsea UK identified specific activities that are a high priority for the aquaculture industry. As well as technical knowledge, the use of testing infrastructure, such as wave tanks, can assist in during the development of new or improved technical solutions.[16]

- Define hydrodynamic loading regime on pen/mooring line systems for more exposed offshore locations
- Reduce seabed footprint of moorings
- Develop new and more efficient anchoring systems
- Development of aquaculture specific engineering standards to support design of moorings/anchors in exposed offshore locations
- Improve data available on mooring line forces for aquaculture specific issues.

- *Predator innovation*

Predation of fish in fish farms is a concern due to losses and fish health. The predators vary on geography, such as seals in Scotland, sealions in Tasmania and Wolves in Chile, as well as sea birds. Cages have to be open enough to allow a suitable flow through of water, but strong enough to withstand predator attacks. Other technology can also be used here such as using e.g. acoustics as deterrents.

- *Movement of fish for grading and treatment*

Fish are moved at various points in the lifecycle, such as being moved for the hatcheries into the ocean; whilst undergoing treatment, during size classification and during harvesting. Innovation could be used to improve the technology of the pumps in currently in use to improve mortality rates and reduce the damage and stress that the fish experience. This could also include increased mechanisation in the processing stage of fish farming.

- *Treatment of sea lice*

SubseaUK identified a number of opportunities around the prevention and treatment of sea lice in finfish, which is considered a high priority area, particularly in relation to non-chemical treatments. [16]

- Non-intrusive methods of counting and removing sea lice on finfish
- Investigate the use of acoustic and electric field methods to delouse finfish
- Investigate enhanced mechanical methods of lice removal (including thermal methods)

A novel solution that has been proposed by Hauge Aqua, a Norwegian aquaculture company, who have designed an aquaculture 'egg'

Figure 9: Hague Aqua's proposed enclosed industrial aquaculture product. Source: Hauge Aqua

The principal of the Hauge Aqua's technology, as well as having a controllable environment which works with existing infrastructure such as moorings and supply barges, the system draws water from 20m below it in an area where sea lice are less likely to be viable, thus eliminating them from the water that the fish live in. The system also protects the fish from predators and the geometric shape is designed to withstand ocean forces. [20]

- *Environmental impact*

Fish farms require environmental impact assessments (EIAs) to be carried out as part of the licensing stage. Requirements will vary depending on the country, but all have some level of requirement. Subsea surveys are a strength in the Scottish supply chain and can be used in connection with marine spatial planning tools. Elements that need to be considered include:

- Environmental risk assessments and analysis
- Capacity of coastal environment to assimilate discharges from aquaculture
- Interactions between wild and cultivated species. Escapes from fish farms are a potential cause for concern as they can transfer disease to wild stocks and also pose a threat to wild stocks in terms of cross breeding. This is a matter taken seriously in Norway with fines (NOK500 / £46) applicable for each escaped fish found in a river.[6]

- Better efficiency in inshore sites

There is an opportunity to improve the efficiency and therefore production volume at inshore sites. The Value of Aquaculture in Scotland highlighted a number of opportunities:

[20] Hauge Aqua website, accessed January 2018

- efficiencies in feed production costs;
- new systems for rearing young fish to shorten their time in sea water;
- increases in permitted biomass through a better understanding of the biomass limits of sites;
- and production increases and economies of scale in other aquaculture sectors through co-operation and amalgamations.[5]

- *Submersible solutions*

Submersible sea cages for finfish and shellfish are a potential solution to mitigate the challenges of higher energy environments further offshore. Submersible and semi-submersible cages are already seen in some locations, e.g. for the culture of sea bream in Italy (Refa-med leg tension cages), Pacific threadfin in Hawaii (SeaSpar cages) and cod off New Hampshire. These cages would shelter the fish during storms and provide protection against e.g. escapes and predators. There however, must be rigorous demonstration about the impact of these cages on fish health and growth rates, and fish needs such as access to surface waters to fill their swim bladders.[14]

- *Increased Automation*

Key areas for technology development in Aquaculture seem to be around sensors, as well as materials, HSE and moorings. Aquaculture farms have automated blower feeders which are linked to underwater cameras which detect when the fish are fed to satiation, thus allowing the feed to be stopped and reduce the amount of unassimilated feed lost to the local environment. Research themes around production and disease and pathogen avoidance continues. Aquaculture is capital intensive with 10% more on 'purchases' (equipment, smolts, feed, etc) than within the rest of the sector. A move to offshore sites may lead to a requirement for further monitoring and automation.

SubseaUK identified actions around sensors, automatic monitoring, and intelligent systems, as well as likening the opportunity to the 'Fields of the Future' plans within the oil and gas industry[16]:

- Undertake survey of manually intensive work in aquaculture work tasks to show opportunities for automation
- Develop road map for use of range of sensors for monitoring parameter under computer control
- Investigate sensor networks and communications
- Investigate standards
- Exploitation of computer vision for monitoring tasks

Sensors requirements for aquaculture include[16]:

- water quality (dissolved oxygen, pH, communications conductivity, oxidation/reduction potential, total dissolved solids, turbidity, salinity, temperature, prescribed chemicals), meteorological properties (waves, current),
- net tension and net deformation.
- monitoring fish weight, quality, condition, mortality, speed, and physiological parameters.

4. Global Markets

In 2013, the estimated value of global aquaculture production was US$157bn (£116bn), from a volume of 97 million tonnes live weight.[21] The top ten aquaculture producers in 2015 are listed in Table 5 below, cumulatively they represent 89 percent of global aquaculture production (by quantity) in 2015.

Table 5: Top ten global aquaculture producers in 2015. Source: FAO yearbook 2015

Country	Quantity *(million tonnes)*
China	47.6
India	5.2
Indonesia	4.3
Vietnam	3.4
Bangladesh	2.1
Norway	1.4
Egypt	1.2
Chile	1.0
Myanmar	1.0
Thailand	0.9

As seen in Figure 10, Asia is the predominant aquaculture producer, with 88-89% of the world's fish food production consistently since 2000. The production increases across all continents from 2000-14, however the rate of growth slows gradually post 2010 in most areas, with the Americas and Europe seeing the largest gains in these years.

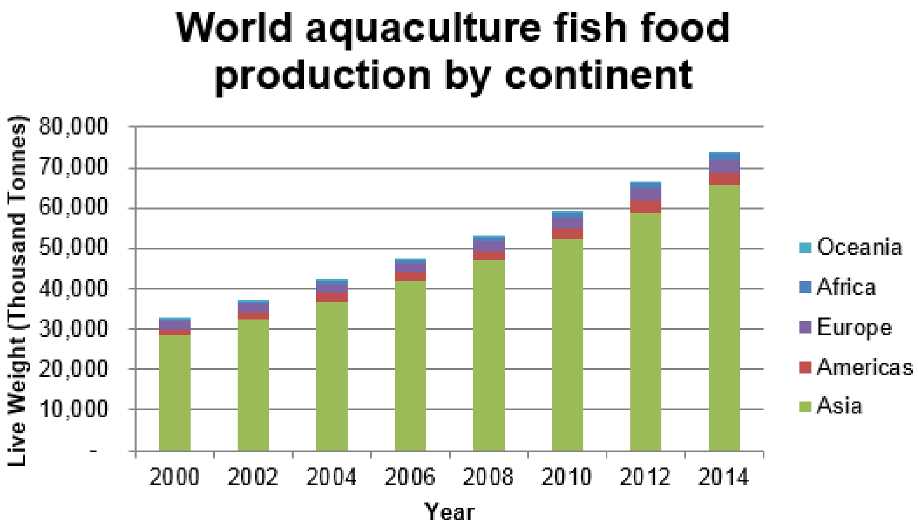

Figure 10: World aquaculture production of food fish by continent. Data source. FAO (FAN#56)

[21] Canadian Council of Fisheries and Aquaculture Ministers (CCFAM), Aquaculture Development Strategy 2016-2019, 2016

In Figure 11, the outer circle shows the share of total fish production by region from 2010 and projected to 2030. In this time, there is a 23.6 percent growth in production. All areas experience a growth in this time except Japan where production falls by 9% over the two decades, due to a large predicted drop in capture (-15.6%) coupled with lowest predicted increase in production from aquaculture (28.7%) across the regions. The largest predicted growth is seen by India which experiences a 60.4% growth from 2010 to 2030, which is driven by a predicted significant increase in aquaculture production (121.1%) and a small increase in wild capture (2.2%). The inner circle shows the split of production between capture (the darker segment) and aquaculture (the lighter segment) for each region. All regions see an increase in aquaculture with the global total predicted to increase by 61.9% from 2010 to 2030, in the same timeframe capture is predicted to reduce by 0.1% globally.

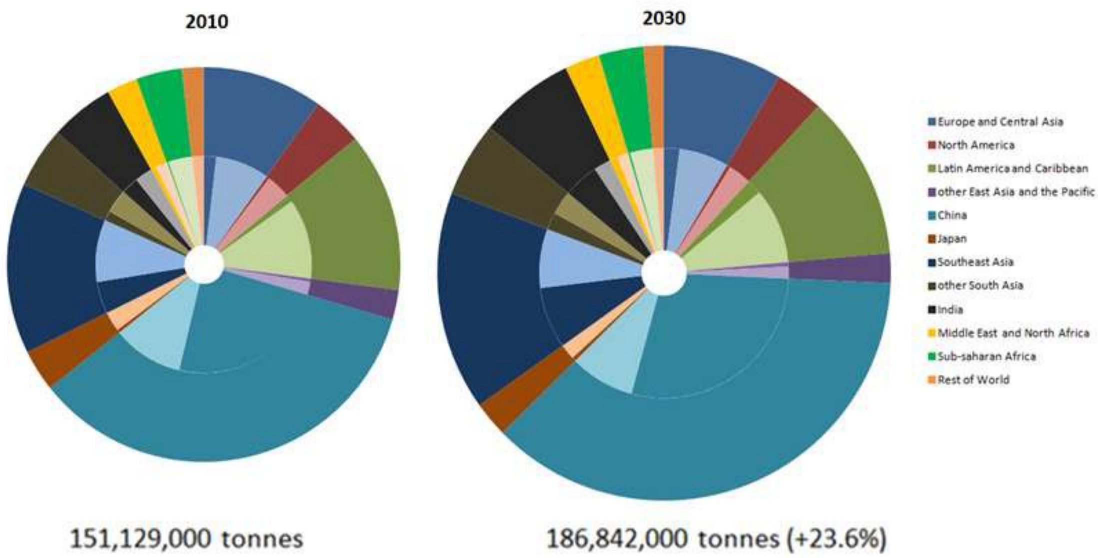

Figure 11: Total Fish Production. Outer circle total fish production per region, inner circle split between capture (darker segment) and aquaculture production (lighter segment). Data source: Fish to 2030, The World Bank.

Table 6 below shows the countries that have been investigated for this report. These have been selected based on their current or potential aquaculture activity and therefore their interest as potential markets for export or collaboration from the Scottish oil and gas subsea engineering sector. The table also includes the main mariculture species, as they are most relevant to technology synergies and any particulars, such as the relative size of the market. More detailed descriptions of these countries' markets are found in the following sections.

Table 6: Overview of the main mariculture species farmed by country. Source: various

Country	Main Mariculture Species	Notes
China	Molluscs and aquatic plants	Largest aquaculture market – but almost entirely freshwater aquaculture, such as Carp.
India	Crustaceans	
Australia	Tuna and salmon	
United Kingdom	Salmon	Third largest salmon producer in the world
Norway	Salmon and trout	Biggest salmon producer globally
Turkey	European seabass and gilthead	Biggest seabass producer and exporter.

	seabream	Second biggest seabream producers
Greece	Gilthead seabream and European seabass	Largest seabream producers
Spain	Mussels, gilthead seabream and European seabass	
France	Mussels and Oysters, trout and salmon	
Egypt	Seabass and seabream	
Canada	Salmon	
Chile	Salmon	Second largest salmon producer globally
Brazil	Cobia (*Rachycentron canadum)*; grouper *(Epinephelus marginatus)*; and *Caranx* species	Largely freshwater culture of Tilapia, but some new, recent activity in mariculture

Table 7 shows the length of coastline of known mariculture producing countries and compares this to the level of aquaculture production in the country. The table gives a view of two main points, albeit a crude measure. Firstly, those countries that have the potential to increase the level of aquaculture production due to the 'availability' of coastline e.g. Canada, which for the longest coastline has the least production per km, although this does not take into account climatic conditions of the coastline or other sea users. Secondly, this highlights the countries where there is already extensive use of the coastline for mariculture and therefore the opportunity for increasing production from improved technological solutions such as improved stock density through better waste management or moving farms further offshore into higher energy environments.

Table 7: Comparison of international coastlines and mariculture production. Adapted from: Canadian Aquaculture Industry Alliance/RIAS Inc.

Country	**Marine Coastline (km)**	**Marine Aquaculture production in 2012 (tonnes)**	**Tonnes per km of coastline**
Chile	6,435	1,015,563	157.8
Norway	25,148	1,321,034	52.5
Ireland	1,448	35,451	24.5
United Kingdom	19,717	191,761	9.7
United States	19,924	190,789	9.6
New Zealand	15,134	98,958	6.5
Australia	25,760	70,523	2.7
Canada	79,562	166,250	2.1

4.1. Asia and Pacific

JAPAN has a long history of aquaculture as well as a large market for seafood products. Japan's aquaculture industry, which includes aquatic plants (42 percent); shellfish (34 percent) and finfish (24 percent) was worth US$4.6bn (£3.3bn) in 2015 which accounts for 35% of the value of all fisheries products. By live weight production in 2015 was 1.105 million tonnes equivalent to 23.6 percent of total the fisheries production. Finfish production is approximately 250,000 tonnes.[22] Japan's main mariculture species are yellowtail and greater amberjack (58%); red seabream (27%); and coho salmon (6%).[23]

The Ministry for Agriculture, Forestry and Fisheries (MAFF) is the governing department for aquaculture in Japan. There are a number of laws that have an impact on Japanese aquaculture including: the Marine Resources Development Promotion Act which gives provisions on the general framework of aquaculture, such as species subject to promotion of aquaculture and the environment suitable for aquaculture; the Fishery Act which gives provisions on the right to operate aquaculture in waters provided for use by the public; and the Sustainable Aquaculture Production Assurance Act which governs the improvement of aquaculture areas and prevention of the spread of specified diseases among farm-raised aquatic animals and plants, amongst other laws namely regarding the use of fisheries resources, pharmaceuticals, feed standards and the labelling of aquaculture products.[24]

Japan has an ambition to move into the open ocean for aquaculture their aquaculture industry is already engaging with the oil and gas industry. In 2016 the Nippon Steel and Sumikin Engineering Co. have designed and launched an offshore cage system, with automated feeding and onshore control. The demonstration project is located 3km off the coast of Sakaiminato, Tottori Prefecture and is used for rearing coho salmon. The cage system consists of five 25-metre diameter cages around a central control system which houses two silos for feed, and sits in approximately 15m of water. The feed tanks will hold three to seven days of food depending on the size of the fish, and deliver food to the fish via blowers using compressed air.[25,26]

Aquaculture in CHINA is the largest market in the world with approx. 60% of food fish production[8] and 50.8% of the global market of marine aquatic plants[10]. As has been noted in Section 1 much of the food fish market is dedicated to inland farming of carp.

In terms of mariculture production, recent growth in production has come from growth in two major groups, namely molluscs and aquatic plants, predominantly the brown seaweed *Laminaria Japonica*.[27] Mariculture in China is centred around the mudflats and intertidal zones, and therefore shallow water sites.

The largest predicted growth is seen by INDIA which experiences a 60.4% growth from 2010 to 2030, driven by a predicted significant increase aquaculture (121.1%) and a small increase in capture (2.2%). India's aquaculture is dominated by freshwater farms for Carp, etc. as well as the development of high value species such as rainbow trout mainly in the Himachal Pradesh region. However, there has

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[22] OECD Review of Fisheries: Policies and Summary Statistics 2017, Fisheries and aquaculture production in Japan, 1995-2015, 2017

[23] Maita, M., The state and problems of aquaculture in Japan and development of technology for the solution, 2012

[24] United States/Japan Cooperative Program in Natural Resources (UJNR) Japan Panel, 2015 Annual Report on Aquaculture in Japan, 2015

[25] The Japan Times, Norway and Japan tap cutting-edge tech to start large-scale offshore salmon farming, 2017

[26] The Fish Site, Japan Builds First Offshore Aqua-Farming System, 2016

[27]Yap, W. G., FungeSmith, S., Rimmer, M., Phillips, M. J., Sih Yang Sim, Kongkeo, H. and Bueno, P. B., Aquaculture in Asia-Pacific and the Outlook for mariculture in Southeast Asia, 2005

been an increase in mariculture, largely associated with crustaceans.[8,28,29]

In **AUSTRALIA** growth in aquaculture production has been driven by salmonids in the decade to 2015 (salmonids production increased 185%). 2015 aquaculture production amounted to 89,217 tonnes and contributes 42% to the value of Australia's fisheries and aquaculture sector, an increase from 29 percent in 2005. The main region for salmonids is Tasmania, and production of salmonids is valued at AUS$631m.[30]A notable aspect of the **OCEANIA** aquaculture market is that unlike Northern Hemisphere markets and South America there are no reports of salmonids being affected (seriously) by caligids (sea lice).[31] However, they do have problems with Amoebic Gill Disease (AGD) requiring freshwater and/or Hydrogen Peroxide treatments. Oceania has seen a significant growth of 73% in the production of seaweed from 2010 to 2014.[10]

ASIA accounts for the majority of aquatic plant aquaculture with Indonesia accounting for 30.8% of global marine aquatic plant production. It is the second largest market after China, followed by Philippines, South Korea, Japan and Malaysia which altogether accounted for 94.4% of global marine aquatic plant production in 2013. The Philippines is the third largest producer, but as with Japan, has seen some decline in the production of aquatic plants. [10]

Other key markets for Aquaculture in Asia and the Pacific region include:

- Philippines
- South Korea
- Malaysia
- Solomon Islands
- Bangladesh

Within the Asia and Pacific Region Kiribati, Timor-Leste and India all have potential for a significant increase in production of seaweed according to the FAO (2014).[10]

Asia and the Pacific region, although the major players in aquaculture, have most of their production from freshwater farms and inshore areas. There are therefore less synergies at this point than for other global areas with the subsea oil and gas sector. Technology crossover and advancements made for mariculture may be applicable to freshwater aquaculture, but they are not assumed to be the main market initially. It is worth noting, however, that the aquatic plant production in Asia and the Pacific region may be an important market to consider in the shorter term.

4.2. Europe, Middle East and Africa

Aquaculture accounts for approximately 20% of fish production in Europe, directly employing around

[28] UNFAO, The Bangkok Declaration and the Strategy for Aquaculture Development Beyond 2000: The Aftermath, Japan's Aquaculture, 2001

[29] Singh, A. K., Pandey, N.N. and Ali, S., Current Status and Strategies of Rainbow Trout Oncorhynchus mykiss Farming in India, *International Journal of Aquaculture*, **7**, 2017, p23-30

[30] Australia's fisheries and aquaculture industry: key trends, global context and seafood consumption, ABARES Australian fisheries and aquaculture statistics 2015

[31] CABI, Sea lice (Caligidae) infection of fish, 2017

85,000 people. The sector in Europe is mostly made up of SMEs and micro-enterprises in coastal and rural areas. Aquaculture production in Europe has not grown as quickly as the global rate, with production remaining constant since 2000, compared to a global growth of around 7% annually. Aquaculture from the EU is known for and trades on its high quality, sustainability and consumer protection standards. The EU provides the European Maritime and Fisheries Fund (EMFF) of which 19% (€1.2bn) of the €6.4bn budget is earmarked for Aquaculture.[32] Within aquaculture in the EU28 (2014), 91% of production is from mariculture, and the remaining 9% is from fresh water aquaculture (and other).[33]

NORWAY has a strong heritage in aquaculture, with fish cages, regarded as the worlds first, deployed in the 1970s[6]. The industry in Norway supports 22,700 jobs. EY report that the export value of Norwegian sea farming has more than doubled in the decade from 2006, and now stands at NOK65.5bn (£5.9bn), up from NOK50.1bn (£4.6bn) in 2015. The significant increase from 2015 to 2016 is argued to be due to a supply shortage from Norway and Chile due to disease outbreaks, coupled with favourable exchange rates for selling Norwegian products abroad. In 2012 analysis predicted a total revenue from salmon and trout farming of NOK119bn (£10.8bn) by 2030 and NOK238bn (£21.7bn) by 2050. On current trends, the path to 2030 looks achievable, and with falling revenue from the O&G sector the value of the aquaculture industry could surpass that of O&G by 2050.[18] The Norwegian government is active in promoting the sustainable growth of the Norwegian seafood sector.

The regulation of the Norwegian aquaculture sector is governed by the Norwegian Directorate of Fisheries (NDF). The NDF provide licences, the overall number of which are determined by the Norwegian Parliament, and has the responsibility for managing the Fish Farming Act; Aquaculture Act and implementing political objectives relating to aquaculture.[18] There are three types of licences in Norway:

- *Ordinary licences* which are traded in the open market for NOK50-70m (£4.6 – 6.4m). The first of these licences were issued in 1986 (for free).
- *Green licences* which are similar to ordinary licences, but have greater environmental conditions attached. An open bidding round for 15 of these licences was held in 2014 and were traded between NOK55m - 66m (£5 - 6m).
- *Research and development licences* which were first issued in 2015 and applications for them were accepted until Nov 2017. The licences were designed to encourage innovative solutions to combat sea lice and diseases in the farms. Licences cost NOK10m and will be converted to ordinary licences after the project period. By January 2017 there were 38 applications for these R&D licences, although at the time of the EY report only two applicants had been accepted: Ocean Farming AS (controlled by Salmar ASA) who have been granted 8 licences for their ocean cage technology which is inspired by O&G technology, and Nordlaks Oppdrett AS who have been granted 10 licences for their concept based on a ship.[18]

Norway has the *Exposed Aquaculture Operations Centre* (EXPOSED) the role of which is to develop the

[32] European Commission, EU Aquaculture Online, accessed December 2017
[33] European Commission, Aquaculture Statistics, 2017

competence and technology to address the challenges of moving to high energy aquaculture sites. The centre has six core research themes:

- Autonomous systems and technologies for remote operations
- Monitoring and operational decision support
- Structures for exposed locations and
- Vessel design for exposed operations
- Safety and risk management and
- Fish behaviour and welfare.

The first four points target technological innovations that are necessary for operating safely and reliably in the high energy sites, the final two points are crucial for the sustainable production of the fish. EXPOSED has also instigated a project around scenario mapping for the technological concepts and structure of the aquaculture industry.[34,35]

As well as fish production, Norway is ranked within the top ten aquatic plant producers globally, even with a recent decline in production (one of only two non-Asian countries in the top ten, the other is Zanzibar (0.4%)) it has 0.6% of production.[10]

MADAGASCAR and **MOZAMBIQUE** are believed to have the potential for significant aquatic plant industry growth. Mozambique however has stopped production due to non-technical reasons (marketing).[10]

Within the area of the General Fisheries Council of the Mediterranean (GFCM) there are six main mariculture countries:

- Turkey, where the main species is European seabass (*Dicentrarchus labrax*),
- Greece, where the main species is gilthead seabream (*Sparus aurata*)
- Egypt, where the main species is mullets (*Mugilidae* spp)
- Spain, which is more dominated by molluscs than finfish, has the main species of Mediterranean mussels (*Mytilus galloprovincialis*), alongside sea bass and seabream
- France, the Pacific oyster (*Crassostrea gigas*)
- Italy, the Japanese carpet shell (*Ruditapes philippinarum*).[36]

Of these mariculture countries, Turkey, Greece and Egypt, pose the greatest interest in terms of synergies with the subsea engineering supply chain.

GREECE is ideally situated for marine aquaculture with favourable climatic conditions and sheltered conditions within the island archipelago to protect the farms from the worst of the weather. Aquaculture production in Greece is dominated, both in volume and value, by marine aquaculture, with gilthead seabream, European seabass and mussels making up 97% of the production total.[11] The mariculture farms are largely located in the island blocks of Dodekanissa, Euvoia, Kefalonia-Ithaki and in the sea areas of Thesprotia, Fthiotida and Aitoloakarnania.[37]

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[34] H. V. Bjelland *et al*., "Exposed Aquaculture in Norway," *OCEANS 2015 - MTS/IEEE Washington*, Washington, DC, 2015, pp. 1-10.
[35] Annual Report 2016, EXPOSED, 2017
[36] General Fisheries Commission for the Mediterranean, Indicators for sustainable aquaculture in Mediterranean and Black Sea countries, Studies and Reviews, 2013
[37] European Maritime and Fisheries Fund, Greece's Operational Programme, 2013

In 2013, the value of aquaculture in Greece was €639m (approx. 145,000 tonnes). The aquaculture sector in Greece employs around 4,900 people. By value, the biggest contributor to the sector are the hatcheries and nurseries of marine finfish. The Greek multiannual national strategy for aquaculture states that Greece is looking to increase its production by 49% from 2012 (114,000 tonnes) to 2020 (170,000 tonnes). Aquaculture products are Greece's primary export and so growth in this sector has an important impact on the economy. Greece has potential for growth in the aquaculture sector and boasts not just the right sea conditions but also the scientific knowledge, trained personnel and infrastructure. They are looking to develop through innovation and ensure high quality products as well as environmental sustainability.[37,38]

TURKEY is the leading aquaculture producer in the Mediterranean, farming large quantities of European Seabass (75,164 tonnes), gilthead seabream (51,844 tonnes) and trout (6,872 tonnes of sea-raised trout (freshwater rainbow trout is produced as well)). Activity occurs in the Black, Aegean and Mediterranean Seas, across 520 marine aquaculture facilities, which are increasing by 60-70 new facilities each year, and supports approximately 25,000 jobs. Turkey produced 240,334 tonnes of aquaculture products in 2015 (36% of the total fish produced). The capture and aquaculture products had an export value of €692m (£616m) in 2015. The industry in Turkey is supported by government strategy and research and development in the sector. The Turkish sector also includes the culture of tuna stocks in Aegean Sea. In 2007, much of the Turkish aquaculture sector relocated offshore to minimize the conflict for space in the coastal areas. This move has also boosted productivity and it is projected that production will double by 2023 to 500,000 tonnes. There are still challenges to be overcome in the sector, although progress is being made through widespread uptake of e.g. ISO 14000 standards. Further work must be done to improve infrastructure for supplying feed and other raw materials to the farm as well as training of personnel. Investment is therefore needed to improve the economic performance of the sector.[39]

Governance of aquaculture in Turkey is through the Directorate General of Fisheries & Aquaculture Products in the Ministry of Food, Agriculture & Husbandry. All producers must have a licence from the Ministry of Food, Agriculture & Husbandry. For growing farms and hatcheries of trout, carp, seabass and seabream with a capacity of up to two million fry/year applications can be submitted to the Provincial Directorates, all other applications must go directly to the Directorate in Ankara.[40]

In the **UNITED KINGDOM**, the majority of aquaculture activity (96%) occurs in Scotland, and is focussed around Atlantic salmon. The industry has a vision to double turnover to £3.6bn (from £1.8bn in 2016) and employment numbers to 18,000 by 2030.[41] Exports from the aquaculture industry are thought to be worth £541.2m. In 2016-17 these exports were estimated to account for 58.7% of industry revenue [IBISWorld], this is a figure that has grown from 49.3% in the past five years, and is expected to keep growing. The growth here can be attributed similarly to Norway, in terms of the reduced supply due to disease outbreaks in Chile and Norway. Scotland's farmed salmon also holds

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[38] European Commission, Greece: Multiannual national plan for the development of sustainable aquaculture an overview, 2013
[39] Eurofish, Overview of the Turkish fisheries and aquaculture sector, 2015
[40] Innovation Norway, Turkish Aquaculture Sector, 2012
[41] Food and Drink Scotland, Aquaculture Growth to 2030, A strategic plan for farming Scotland's seas, 2016

Protected Geographical Indicator (PGI) status which shows criteria set by the European Commission have been met and ensures a certain standard, increasing desirability. The largest markets for Scottish salmon are the USA and Europe.[4]

There is limited cultivation of aquatic plants in the UK, but there is active research into the scaling up of macroalgae aquaculture in Scotland (SAMS, Oban and UHI, Shetland), Northern Ireland (Queen's University, Belfast) and Wales (Swansea University). Trial cultivation of *Saccharina latissima* and *Laminaria hyberborea* is underway at two sites in the Shetland islands.[42] Scotland is also home to the internationally respected Scottish Association of Marine Science (SAMS) who are conducting various research projects into the cultivation of seaweed through aquaculture, such as the GlobalSeaweed project.[43] There is an opportunity to increase the macroalgae production in the UK, due to the climatic conditions and extensive coastline, but this would have to be through aquaculture as wild harvest is at its maximum for current locations.[10]

The *Aquaculture Growth to 2030* industry vision report highlights within its lead recommendations the need for the "Development of Innovation Sites in Scotland". The recommendation will be managed by the industry leadership group (ILG). The purpose of the recommendation is to ensure that there is the opportunity to trial and develop innovative solutions to the challenges that aquaculture faces at present such as the development of new equipment and technology or disease control measures. The recommendation therefore shows the need for regulators to take a risk based approach to permitting new technologies, along with the provision of Innovation Sites, to allow for in-field trials assuming suitable EIA requirements are met.[41]

In SPAIN aquaculture is a diversified sector, with approximately thirty different species cultivated. In 2014 the Spanish aquaculture sector produced approximately 285,000 tonnes, of which over 90% is from mariculture, which is further split into 85% molluscs and crustaceans and 15% marine finfish. By volume mussels account for approximately 75% of the aquaculture output. The mussels are mostly farmed in Galicia in five bays: Vigo, Ponteverda, Arousa, Muros and Ares, from floating rafts.
The Spanish aquaculture sector is dominated by small to medium sized farms, in 2015, 4,803 of the 4,906 mariculture farms are dedicated to mussels and other molluscs, 96 to marine finfish, 4 for shrimp and 2 for aquatic plants. In terms of marine finfish production, the main species are gilthead seabream and European seabass which are farmed on the Mediterranean coast. There has been recent interest in high-value species such as meagre, tuna and yellowtail, and these should be considered of interest going forward.[44]

Spain's multiannual strategic plan for Spanish aquaculture 2014 – 2020 shows that there is an ambition to grow the aquaculture sector from an economic value of €475m in 2015 to €550m in 2020 and €778m in 2030. This is a volume increase from 267,000 tonnes in 2012 to 320,000 tonnes in 2020 (a 20% increase). By subsector this is an increase in volume of 32% in marine fish farming by 2020 and a 17% increase in volume of mollusc farming by 2020.[45,46] In order to achieve these National Growth

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[42] NetAlgae, Overview of the seaweed industry by country, 2012
[43] Scottish Association for Marine Science, Projects: GlobalSeaweed, accessed December 2017
[44] Eurofish, Overview of the Spanish fisheries and aquaculture sector, 2016
[45] Ecoaqua, Presentation on Spanish multiannual strategic plan, 2015
[46] European Commission, Spain: Multiannual national plan for the development of sustainable aquaculture an

Objectives, there needs to be development of the Spanish system including:

- A simplified regulatory system: aquaculture is administered by each of the autonomous regions, with different requirements in each region. Work is therefore being done on unifying aquaculture regulations for applying for licences; unifying tax, port and waste disposal rules; harmonising EIA requirements and improving aquaculture information systems.
- A coordinated approach to spatial planning: recognising common criteria for the identification of aquaculture areas of interest; develop a Geographical Information System (GIS) for use in marine spatial planning; support investment in new sites and identify and characterise interactions between fish farms and Natura 2000 sites, with the aim of replicating positive interactions.
- Enhance competitiveness: improve the sustainability of Spanish fish farms; boost research and development activities particularly involving SMEs and promote training and the coordination of training between providers.
- Level playing field: Improve collaboration providing co-financing opportunities around enhanced production and improve national and international marketing of Spanish aquaculture products.[46]

Spain also harvests aquatic plants, although this is mostly from wild resource harvesting, a small amount (50 tonnes, <1% of the total harvested) is farmed. The aquaculture produced macroalgae is situated in the region of Galicia, farming *Laminaria ochroleuca* and *Undaria pinnatifida*.[42]

By volume FRANCE produced 691,000 tonnes of fish in 2014, of which approximately 30% was from aquaculture, 155,000 tonnes of shellfish (22%) and 50,000 tonnes of finfish (8% of total). By value, aquaculture products make up approximately 40% (€730m) of a total value (€1,836m). Aquaculture activities are shown to favour higher value fish, due to the increased investment required, and so show that although farmed finfish make up under 8% of the total by weight, they account for slightly over 10% by value.

Shellfish are the biggest portion of mariculture in France, with quantities roughly equal between mussels and oysters (alongside a small number of other bivalves). By value oysters account for 72% (€388m), mussels for 26% (€139m) of the €541m total. For finfish, 83.3% of the volume is from mariculture, and 16.7% from freshwater farming (carp, etc.). The main mariculture species are trout and salmon (€120m, 65.2%) and seabass, seabream and other marine fish (€35m, 19%).[47]

France's multiannual strategic plan for aquaculture shows that they have significant ambitions for mariculture growth. From 2014 to 2020 France aims to increase their overall aquaculture volume to 265,000 tonnes (a 22% increase) and the production value to €1,025m (50% from baseline average of 2007-12). They will do this by increasing the volume of molluscs by 12% by 2020 and their volume of freshwater fish by 28%. These figures are significantly overshadowed by the 233% growth aimed for in mariculture farming.[48]

overview, 2013

[47] FranceAgriMer, Key Statistics, The fisheries and aquaculture sector in France, 2017

[48] European Commission, France: Multiannual national plan for the development of sustainable aquaculture an overview, 2013

France produces almost 60,000 tonnes of seaweed per year, currently only 50 tonnes of this is from seaweed aquaculture. The main area for harvesting wild seaweeds is Brittany, with *gelidium* being produced in the Basque country. There has recently been an increase in the production of seaweed in France.[10,42]

EGYPT is the main aquaculture producer in Africa, with 4 out of 5 African fish farms based in the country. Aquaculture supplies 77% of fish in Egypt, although of this only approximately 3 percent is mariculture. Aquaculture has a value in excess of $2bn to the Egyptian economy and provides over 580,000 jobs. The main aquaculture product in Egypt is Tilapia, where they are second only to China in terms of production, although this serves the local market. They also produce a number of carps and mullets in freshwater aquaculture.[49]

Mariculture occurs in the Mediterranean and Red Seas and also the Suez Canal. The main species produced are flat head grey mullet (*Mugil cephalus*), European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*). Only ten aquaculture companies have permission to sell into the EU, all of which are mariculture companies. The growth of the marine aquaculture sector is therefore seen as an important sector for the economy as it leads to export markets, where the freshwater cultivation is entirely for a local market. Egypt accounts for approximately 70% of north African mariculture as north African countries are still reliant on harvesting wild stocks rather than aquaculture production.[49]

In 1982, the Egyptian government established the General Authority for Fish Resources Development (GAFRD), a specific authority to control aquaculture activities, and a subdivision under the ministry of agriculture. GAFRD is responsible for issuing aquaculture licences and implementing relevant legislation.[Error! Bookmark not defined.]

Aquaculture has developed rapidly in the last two decades and in the last three years there has been a national and governmental drive towards developing Egyptian mariculture. Projects have been established beside the Suez Canal in 2016. There are also projects in Lake Gilion and East Port Said for the production of sea bream, sea bass, mullet and shrimp.[49]

Other EMEA aquatic plant producing countries include: Iceland, Morocco and Russia.[10]

4.3. Americas

CHILE is the biggest aquaculture market in the Americas and it is the second biggest salmon producer globally (behind Norway). In 2011 salmon and trout exports accounted for 3.6% of Chile's total exports and was worth $2.9bn at a volume of 385,000 tonnes.[50] The market has grown and in 2016

[49] Shaalan, M., El-Mahdy, M., Saleh, M. & El-Matbouli, M., Aquaculture in Egypt: Insights on the Current Trends and Future Perspectives for Sustainable Development, *Reviews in Fisheries Science & Aquaculture*, **26(1)**, 2018, 99-110

[50] The Fish Site, Chilean Fish Exports Making a Big Comeback, 2012

Chilean aquaculture exports weighed 800,000 tonnes and were valued at $4.5bn.[51] The Chilean aquaculture industry, however, has suffered a number of set backs including an outbreak of Infectious Salmon Anaemia (ISA) in 2007 which reportedly reduced production by 75% from 400,000 tonnes to 100,000 tonnes from 2005 to 2010.[52] More recently there has been an outbreak of a harmful algal bloom that affected farms in Chile in 2015. This is believed to have been caused in part by the El Niño warming the waters combined with nutrients that have run off agricultural lands into the bays and fjords used by the salmon farmers facilitating the harmful algal bloom. The result was a ban on salmon farming in some regions, causing a reduction in production, worth approximately €800m.[4,51]

Chile's aquaculture industry is almost entirely based on export, with the US and Japan being the main markets. Aquaculture accounts for 62.9% of fishing exports based on weight and 81.9% based on value. The industry is populated by large vertically integrated companies who employ state of the art technology and processes. The activity is based largely in the south of the country, primarily in the Los Lagos region and those south of it. The Chilean government are considering the promotion of farms further north in the country (where capture fishing has been more prevalent) and also to open the market to SMEs.[12]

There is an Association of Salmon Farmers in Chile, SalmonChile, which has a technical branch, INTESAL. This arm of SalmonChile coordinates and carries out R&D activities within the industry. As a globally focused industry due to the focus on export, there is a willingness to embrace technology development. Some examples of this include a move from juvenile and smolt production in natural lakes into recirculation systems to improve production and control. As described above the Chilean aquaculture industry has encountered some issues in recent years, but the development of new technology solutions alongside the development of improved regulations will help create a sustainable aquaculture industry in Chile.[12] There is also growing concern from some of Chile's biggest export markets about the amount of antibiotics used in their production processes, the USA for example is looking for antibiotic free farmed salmon.[53]

Aquaculture in Chile is governed by the Ministry of Economics Development and Tourism through the Undersecretariat for Fisheries and Aquaculture (SUBPESCA) and the National Fisheries and Aquaculture Service (SERNAPESCA), an independent service which controls the activities and regulations for the fisheries and aquaculture sector. SUBPESCA is responsible for granting sites and legally establishing companies as aquaculture operators. Information which regulations are based on is produced by the Fisheries Development Institute (IFOP).[12]

For aquatic plants, Chile is the only American country in the top ten producers list. In 2013 it produced 2% of the global production. Elsewhere in the Americas, Mexico has seen a significant increase in production.[10]

Aquaculture in CANADA generates CAN$2bn (£1.2bn) in GDP, with a production volume of 200,565 tonnes valued at CAN$1.37bn (£811m). Aquaculture accounts for 16% of Canada's total seafood

[51] DAC Beachcroft, Challenges faced by Chile's aquaculture industry, 2017
[52] Asche, F., Hansen, H., Tveteras, R. and Tveterås, S., The Salmon Disease Crisis in Chile, *Marine Resource Economics* **2009** 24 (4), 405-411
[53] National Fisherman, Demand for antibiotic-free foods may put pressure on fish farms, 2017

production, and 33% by value. The aquaculture industry in Canada supports a workforce of 25,500 full time workers. Much of Canada's aquaculture industry is focused towards export, largely to the USA (97%) but also Japan, China and Singapore. Over 56% is exported with a value of CAN$1bn (£600m).[54]

Over 45 different species of finfish, shellfish and marine algae are produced in Canada, the main high-volume species are: Atlantic salmon, rainbow trout, blue mussels, oysters and clams. Atlantic salmon accounts for, on average, 70 per cent of volume and 84 percent of total aquaculture value. Over half of aquaculture activity occurs in British Columbia (56.2%) with significant activity happening in the east coast provinces (New Brunswick, 16.9%; Nova Scotia, 8.2%; Newfoundland and Labrador, 7.4%; and Prince Edward Island, 5.6%) as well.[21]

The Canadian Council of Fisheries and Aquaculture Ministers (CCFAM) published the Aquaculture Development Strategy 2016-2019 which highlights Canada's ambitions for Aquaculture. The three outcomes expected from the strategy are:

- An improved federal/provincial/territorial regulatory framework
- Improved coordination of aquaculture fish health management
- Improved support for regional economic growth through aquaculture

Aquaculture in BRAZIL is largely dominated by freshwater aquaculture (82%) where the main species is tilapia (54%), tabaqui and tambuca. There is an ambitious government proposal to significantly increase aquaculture production. By 2020, the Brazilian government wants to increase production from approximately 500,000 tonnes to 2 million tonnes. In order to achieve this US$160m is being offered in the period 2015 – 2020, of which US$2.5m is for technology development. The 1.5 million tonne increase that is targeted would be worth US$2.5bn to the Brazilian economy.[55,56] There has also been an interest from the Ministry of Fisheries and Aquaculture of Brazil to promote mariculture, particularly in the region around Rio de Janeiro. The Ministry has created a series of research and social programmes, facilitating regulatory policies and subsidizing regional hatcheries. The species targeted include: cobia, grouper and Caranx species. Projects that are currently ongoing include a marine fish hatchery; a demonstration unit; and an experimental integrated multi-trophic aquaculture (IMTA) system.[57]

[54] Canadian Aquaculture Industry Alliance, Industry by the numbers, accessed December 2017
[55] Matias, F., Brazil: A new super power in aquaculture, Susaqua Project, 2014
[56] Prado, R., Innovation Norway, Aquaculture Overview – Brazil, 2015
[57] Rombenso. A., Lisboa, V. and Sampaio, L. A., Mariculture In Rio De Janeiro, Brazil, *Global Aquaculture Alliance*, Technical Report, 2014

Annex: List of Acronyms

AGD	Amoebic Gill Disease
CCFAM	Canadian Council of Fisheries and Aquaculture Ministers
Cefas	Centre for Environment, Fisheries and Aquaculture Science (UK)
EIA	Environmental Impact Assessment
EMEA	Europe, Middle East and Asia
EMFF	European Maritime and Fisheries Fund
EXPOSED	Exposed Aquaculture Operations Centre
FAN	FAO Aquaculture Newsletter
GAFRD	General Authority for Fish Resources Development (Egypt)
HDPE	High-Density Polyethylene
ILG	Industry Leadership Group (UK)
IMTA	Integrated Multi-Trophic Aquaculture
ISA	Infectious Salmon Anaemia
ISO	International Standards Organisation
MAFF	Ministry for Agriculture, Forestry and Fisheries (Japan)
NDF	Norwegian Directorate of Fisheries
O&G	Oil and Gas
PGI	Protected Geographical Indicator
R&D	Research and Development
SERNAPESCA	National Fisheries and Aquaculture Service (Chile)
SUBPESCA	Ministry of Economics Development and Tourism through the Undersecretariat for Fisheries and Aquaculture (Chile)
UN FAO	United Nations Fisheries and Agriculture Organisation