Review of Recirculation Aquaculture System Technologies and their Commercial Application

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EXECUTIVE SUMMARY

Recirculation aquaculture systems (RAS) are designed to minimise water consumption, control culture conditions and allow waste streams to be fully managed. They can also provide some degree of biosecurity through measures to isolate the stock from the external environment. RAS technology has steadily developed over the past 30 years and is widely used for broodstock management, in hatcheries and increasingly for salmon smolt production. By comparison, the progress of RAS for grow-out to market size products has been more restricted and there is a substantial track record of company failures both in the UK, Europe and internationally. The reasons for this are varied, but include challenges of economic viability and operating systems at commercial scales.

In spite of this history, several technology companies present a hard sales pitch and claim to have successfully delivered numerous commercial RAS farms targeting a range of species, when in reality the farms may have ceased to exist or production levels are quite insignificant (<100 tonne pa). Much of the RAS technology available on the market and now promoted for marine fish production is based on early systems designed for freshwater species including those that thrive happily in water quality that can be lethal to more sensitive marine species. Some failed commercial RAS were based on experimental research projects producing between 5-20 tonnes pa and then scaled up for commercial production by engineers lacking any credible experience of industrial aquaculture. Without appropriate input, RAS technology providers may not appreciate the potential risk of pathogen ingress to RAS farms and fail to include adequate disease control technology in their RAS design. Equally, experienced aquaculturists do not necessarily have the experience for dealing with industrial scale flows of farm water that requires purification to the high standard required for efficient re-use. Even so, investment is continuing and RAS farms for a variety of species and scales are operating. Most notably there is increasing activity and commercial investment targeted at producing market size salmon in RAS. Key current examples are in the USA, Canada, China, UAE, Denmark and potentially Scotland.

This review considers the current status of RAS technology and its commercial application with particular reference to its potential impact on Scottish aquaculture. With increased reliability and efficiency new opportunities are open to the Scottish industry to both enhance salmon production and diversify to other species. On the other hand, the greater flexibility in locating RAS farms could present a threat to some salmon production in Scotland where production can move closer to key centres of consumption – either in the UK or abroad. After all, one of the environmental advantages of RAS is to enable production in areas unsuited to other forms of aquaculture and where promotion of sustainability is a key element. Consequently, farming close to markets, thereby reducing food miles, may have benefits for both the retailer and consumer. However, what proportion of caged salmon production might eventually be substituted by land based RAS is debateable. This may depend on the economic advantage to some current salmon export markets farming salmon in their own country using RAS technology developed in Europe or North America.

This report recommends a cautious but positive approach towards the adoption of RAS technology, based on clear appraisal of technical and economic criteria. The UK cage salmon sector for instance might increase its focus on optimising the use of RAS technology for smolt production and implementing head-starting methods to optimise production processes (i.e. producing intermediate-sized salmon for cage-fattening) and to alleviate pressure on sensitive coastal habitats where user conflicts are identified as significant.

The benefits of RAS, as an alternative to cage production of salmon, needs to be assessed based on business economics while also taking into account the social and broad environmental (rather than selective) impact of both production methods. If the UK is to increase its sustainable seafood supplies it might consider utilising RAS technology to substitute some of the overseas imports rather than challenging another UK production method to produce the same species. If cage and RAS production technologies try to out-compete each other on sustainability criteria then imported seafood, with unknown environmental credentials, will likely be the winner.

Drawing on the lessons from previous ventures, RAS businesses should not be overly dependent on expected price premiums since these may only be secured for a small fraction of the production. This premium market might weaken as increased RAS production develops close to the main markets within the UK or abroad.

Considering energy use is a major factor in RAS, investors promoting RAS technology for commodity species like salmon might sensibly focus on securing a significant contribution to their energy supplies from sustainable sources to prove their environmental credentials. Scotland might be strategically better placed than other areas to address this objective.

RAS farms are able to better manage effluent waste and this is a key argument in the favour of this production technology. Irrespective of whether the farm is marine or freshwater the waste has a real economic value and an increasing range of recycling options is available. However, RAS investors rarely present properly researched plans and investment for utilisation of farm waste which quickly becomes a management problem as production expands.

While RAS technology has advanced significantly in recent years there remain several water quality treatment and effluent management issues which remain incompletely understood. These particularly refer to RAS farms using >90% water recirculation (< 10% replacement per day) which is really the minimal level required for efficient operation. Equally, the technology available for monitoring the number and range of RAS water quality parameters in real time requires significant improvement

RAS technology is developing and new water treatment processes are being tested, particularly with respect to dissolved nitrogen, carbon dioxide and organic taint compounds. Properly designed and managed RAS are increasingly commercially viable for high unit value species or life stages. The economic bar to the use of RAS will gradually be lowered as technology improves and energy and other efficiencies are realised. This is likely to include some scale economies both in capital and operating costs, although for the present, system design and location appear to be more important.

The use of RAS technology is already increasing in the Scottish salmon industry and further investment in this area will almost certainly be essential for the successful future of the industry. There is a long-term threat to the industry from RAS technology being adopted closer to major markets, but this should be seen as an incentive to continue to innovate for cost competitiveness and diversification using the natural resources available in Scotland.

1 Introduction

1.1 Background

Recirculating Aquaculture Systems (RAS) are intensive, usually indoor tank-based systems that achieve high rates of water re-use by mechanical, biological chemical filtration and other treatment steps. Precise environmental control means aquatic species can be cultured out with their normal climatic range, allowing operators to prioritise production goals linked to market, regulatory or resource availability criteria. For example RAS technology can be useful where ideal sites are unavailable e.g. land or water space is limiting, where water is in short supply or of poor quality, if temperatures are outside the optimum species range or if the species is exotic. It can also be employed when environmental regulation demands greater control of effluent streams and biosecurity (exclusion of pathogens and/or retention of germplasm) or where low-cost forms of energy are available. The ability to maintain optimal and constant water quality conditions can also bring animal welfare gains. Market benefits include increased ability to match seasonal supply and demand, to co-locate production with consumer/processing centres and linked to this improved traceability and consumer trust.

RAS culture is also compatible with many contemporary goals for sustainable aquaculture including the EU strategy for sustainable aquaculture 2009[1]. Many environmental groups support RAS over open-production systems (e.g. marine or freshwater cage production) for the same reasons. Other proponents include providers of equipment and technical services including universities with research and extension programs focusing on RAS. Others attribute biosecurity and potential food-safety benefits to RAS[2].

However investors in commercial RAS still face many challenges. High initial investment and operational costs make operations highly sensitive to market price and input costs (especially for feed and energy). As table-fish tend to have lower unit value compared to juvenile life-stages (e.g. smolts) or products such as sturgeon caviar, their profitable production requires much higher operational carrying capacities. Despite ongoing technological improvement, at these production levels challenges linked to filtration inefficiencies and associated chronic sub-lethal effects of metabolic wastes (NH_4, NO_2 and CO_2) remain key design challenges. Consequently table-fish production in RAS still represents a high risk investment evidenced by their poor long-term track record for lenders.

RAS systems are commonly characterised in terms of daily water replacement ratio (% system volume replaced by fresh water over every 24 hours) or recycle ratios (% total effluent water flow treated and returned for reuse per cycle). For a fixed water supply, increasing recycle ratios above 0% (open-flow) corresponds with an exponential increase in production capacity with greatest gains achieved at rates above 90%. By convention 'intensive' or 'fully-recirculating' RAS are typically defined as systems with replacement ratios of less than 10% per day. Conversely systems with higher replacement rates can be characterised as 'partial-replacement' systems. Partial replacement is commonly used to intensify rainbow trout production in raceways and tanks. Such systems require limited, often modular water-treatment installations and therefore much lower levels of capital investment compared to intensive-RAS. Management goals are also likely to differ; partial-replacement may be most appropriate where water availability or discharge consents are limiting whereas intensive-RAS offer greater scope for heat retention for accelerated growth, biosecurity and locational freedom. For these reasons intensive RAS are also more likely to be established as fully contained 'indoor systems'. As experience has demonstrated, pumping costs are generally likely to be prohibitive for

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[1] "Building a sustainable future for aquaculture, A new impetus for the Strategy for the Sustainable Development of European Aquaculture"
[2] SUSTAINAQ http://ec.europa.eu/research/biosociety/food_quality/projects/181_en.html

partially recirculating, pump-ashore salmon systems, the scope of this report is limited to intensive fully-recirculating RAS options (whilst observing that increasing environmental regulatory pressure is also driving progressive intensification of existing flow-through systems).

1.2 Objectives

The content of the study is set out in the terms of reference as follows:

- Historic development of RAS technologies
- Description of current range and variety of RAS operations
- Appraisal of short to medium term prospects of commercial viability of RAS operations for production of Atlantic salmon for the table
- Appraisal of short to medium term prospects for commercially viable operation of RAS in the HIE area producing one or more species (fin fish, shellfish, algae etc.)
- Appraisal of short to medium term implications for the HIE area in scenarios where commercially viable RAS operations are established in the UK and/or overseas.

1.3 Approach

The report was based on

- A review of secondary literature
- telephone survey of key informants associated with the salmon and RAS sectors (Table 1)
- Case study research based on documentation and interviews with those directly involved with recent as well as failed historic start-ups
- The authors direct experience of commercial culture of various species in RAS

Table 1: Summary of key informants by specialisation and species of interest

Specialisation	**Location**	**Species**	**No Respondents**
Aquaculture RAS insurance under-writer	International	Salt& fresh water	1
RAS owner/operators	UK & Europe	Salt & fresh water	5
Aquaculture engineering company	UK	Salt & fresh water	2
Environmental certification	UK	Salmon	2
Fish genetics academic expert	UK	Salt & fresh water	1
Other academic and industry experts	Europe	Salt & fresh water	4
Total			15

2 Historic development of RAS technologies

2.1 Origins

The earliest scientific research on RAS conducted in Japan in the 1950's focussing on biofilter design for carp production was driven by the need to use locally-limited water resources more productively. Independently of these efforts, European and American scientists attempted to adapt technology first developed for domestic waste-water treatment (e.g. the sewage treatment activated sludge process, submerged and down-flow biofilters, trickling and several mechanical filtration systems). These early efforts included work on marine systems for fish and crustacean production. Despite a strong belief by pioneers in the commercial viability of their work, most studies focussed exclusively on the oxidation of toxic inorganic nitrogen wastes derived from protein metabolism to the exclusion other important excretion issues. Furthermore, most of early trials were conducted in laboratories with very few at pilot scale. Their belief was buttressed by the successful operation of public and home aquaria but overlooked the fact that because of the need to maintain crystal clear water, treatment units in aquaria tend to be over-sized in relation to fish biomass; whilst extremely low stocking levels and associated feed inputs meant that such over-engineering still made a relatively small contribution to capital and operational costs compared to intensive RAS. Consequently changes in process dynamics associated with scale-change were unaccounted for resulting in under-sizing of RAS treatment units in order to minimise capital costs. As a result safety margins were far too narrow or none-existent.

Despite this partial understanding many companies sold systems that were bound to fail resulting in scepticism amongst investors from the onset and delays in further technical improvement. Some simple but costly early problems were relatively easy to redress whilst others have proved more intractable. Many operators knew the volumes of their culture tanks, but not their systems, complicating basic mass-balance calculations required for day to day operation. Sumps were also frequently mis-sized resulting in flooding or pumps running dry. Some idea of the scale of the knowledge deficit during this early phase of development can be had by comparing the upper operational biomass stocking densities achieved in experimental RAS (10 - 42kg/m^3) and commercial RAS (6.7 - 7.9kg/m^3). By contrast, modern commercial RAS are expected to support densities of 50 to >300 kg/m^3 contingent on species and limiting factors associated with design choices (e.g. aeration v oxygenation). For reference, typical upper limits in public aquaria range from 0.16 - 0.48kg/m^3, though as indicated earlier, high stocking densities are not a management goal.

As many of the pioneering scientists had biological rather than engineering backgrounds, technical improvements were also constrained by reporting inconsistencies and ad-hoc definitions resulting in mis-communication between scientists, designers, construction personnel and operators. Development of a standardised terminology, units of measurement and reporting formats in 1980[3] helped redress the situation, though regional differences still persist. For example recycle ratio rather than replacement rate (Section 1.1) remains the favoured term in the USA. As the former 'ratio' definition lacks a time dimension its misapplication could result in serious under or over-estimation of treatment requirement estimates (as the dimensioning of biological-filtration requirements and ultimately biomass limits are more directly linked to feed input rather than stocking density, there is now also a growing tendency to specify water requirements in relation to maximal feed input levels). Early researchers also envisaged steady-state operation i.e. whereby rates of metabolite production and degradation would equilibrate. It was not until the mid-1980's that cyclic water quality phenomena well recognised in pond production (e.g. in pH, oxygen, TAN (total ammonia

[3]EIFAC/ICES World Conference on Flow-through and Recirculation Systems, Stavanger, Norway 1980 and the 1981 World Aquaculture Conference, Venice, Italy.

nitrogen), NO_2 (nitrate), BOD (Biochemical oxygen demand), COD (Chemical oxygen demand)) were characterised in terms of their amplitude and frequency. Although the efficiency of many treatment processes is concentration-dependent and therefore to some degree self-regulating, response times are highly variable e.g. oxygen deficits improve aerator efficiency immediately whilst the lag-phase for bacterial nitrification adaptation in response to elevated ammonia concentration is much longer. Understanding such variability as interacting limiting production factors now plays a critical role in system design and operation.

The on-going faith of RAS researchers and engineers in narrow technical solutions to problems of commercial viability going forward is illustrated by the strap-line: 'for better profits tomorrow' of *Recirc Today*, a short lived 1990's industry Journal.

2.2 Commercial RAS performance in the UK

Despite considerable technical improvement, economic sustainability has remained elusive and is the greatest challenge for long-term adoption of RAS for table fish grow-out. An objective historical assessment clearly indicates that although the basic technology has now existed for over 60 years now, its application for commercial table-fish production continues to exhibit a 'stop and start' trajectory with many 'sunset' ventures collapsing after only 2-3 years of operation in sequential phases of adoption. Although new-starts, particularly those for novel exotic species regularly make headline news in the aquaculture press, reasons for failures are poorly documented, complicating objective assessments and recurrence of mistakes. This knowledge gap is a consequence of sensitivity over costly failures, communication barriers associated with the fragmented nature of the nascent sector and potential conflicts of interest between technology providers and producers e.g. equipment providers are more likely to emphasise management problems rather than more fundamental design or marketing constraints.

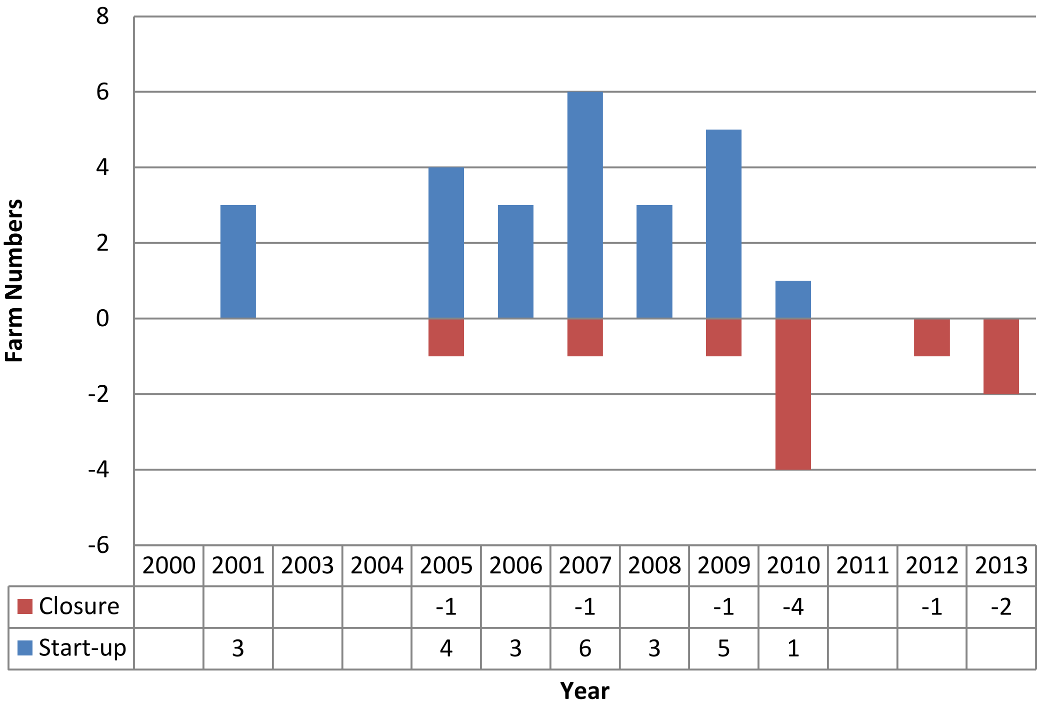
Factors contributing to a lack of profitability include vastly overestimated sales prices or growth rates, at other times system design is fundamentally in error resulting in carrying capacities that are much lower than originally projected. Often equipment is poorly specified or assembled rather than being inherently bad. Unforeseen shifts in critical energy and feed input costs have also contributed to failure.

In the UK, juvenile rather than table-fish production provides the most sustained example of commercial adoption, specifically for the production of juveniles in hatcheries and salmon smolts for cage/pond on-growing. Smolts constitute up to 20% of table-fish whole live farm-gate price, making them a high-value commodity; over three times the value of table-fish in weight terms. At the same-time their production in RAS incurs a relatively small proportion of total salmon production costs. Consequently RAS have made a considerable contribution to increased smolt yields. Sustained adoption of RAS technology elsewhere has been predicated on farming higher-value species such as turbot, eel and sturgeon or production of value-added products for niche markets e.g. production of live tilapia for the ethnic market in northern America.

Exotic tilapia (*Oreochromis niloticus*) was also one of the first candidate warm-water species for commercial scale table-fish culture in the UK. In the early 1990's a joint venture with Courtaulds textiles used waste heat that was a by-product of the manufacturing process to reduce culture costs, selling their stock to Tesco's. Other smaller-scale efforts were based on a similar integration strategy, for example using waste-heat and feed ingredients from distillery operations. In addition to marketing difficulties these efforts eventually failed due to over-reliance on third-party provision of these services; Courtaulds began to charge for waste heat and maintenance schedules for the primary production processes were prioritised over aquaculture

Thereafter other than for hobby-scale efforts, interest in warm-water table-fish production receded until early in the new Millennium when a sequence of commercial start-ups for three key species occurred; tilapia, barramundi and sea bass (Fig. 1) which we will now consider in three case-studies. All were based on fully-recirculating RAS located in England and Wales close to large prospective urban markets. Whereas the latter two species were produced by just two sizeable individual joint ventures, the initial tilapia production figures (Fig 2) include contributions from multiple small-scale start-ups. Nearly all were adopters of a franchise-package offered by a British company called UK-tilapia based in Ely near Cambridge. This involved adopters investing in turn-key production systems nominally capable of producing at least 100t/year designed and installed by UK-tilapia, who also claimed to offer technical support, seed and feed provision and harvest buy-back options. All adopters were individual small-scale investors, mostly mixed-arable and livestock farmers in Eastern England (Lincolnshire, Yorkshire and Durham) seeking diversification strategies for their businesses. Unfortunately UK-tilapia's principle experience lay in seafood marketing rather than RAS design and operation (they had previously acquired a defunct RAS system with its own design problems near Ely). Consequently designs were very basic, incorporating aerated fibreglass or concrete raceways, water and/or air heating, commercial drum-filters and self-designed/constructed up-welling biological filters. All culture treatment units were surface-mounted (i.e. no sumps or buried pipework) to minimise civil engineering costs but at the expense of water-balancing ease and access for husbandry activities. There was also considerable variation in the types and sizes of treatment units procured, and linked to this, apparently ad-hoc levels of modularisation in different installations. Low-cost design simplicity was predicated in part on the resilience of tilapia to turbid water quality conditions. However although capable of survival in 'brown-water', growth performance is significantly compromised. For these reasons the installed systems achieved less than half their design production capacity and most continued to fall far short of this figure even after significant remedial investment.

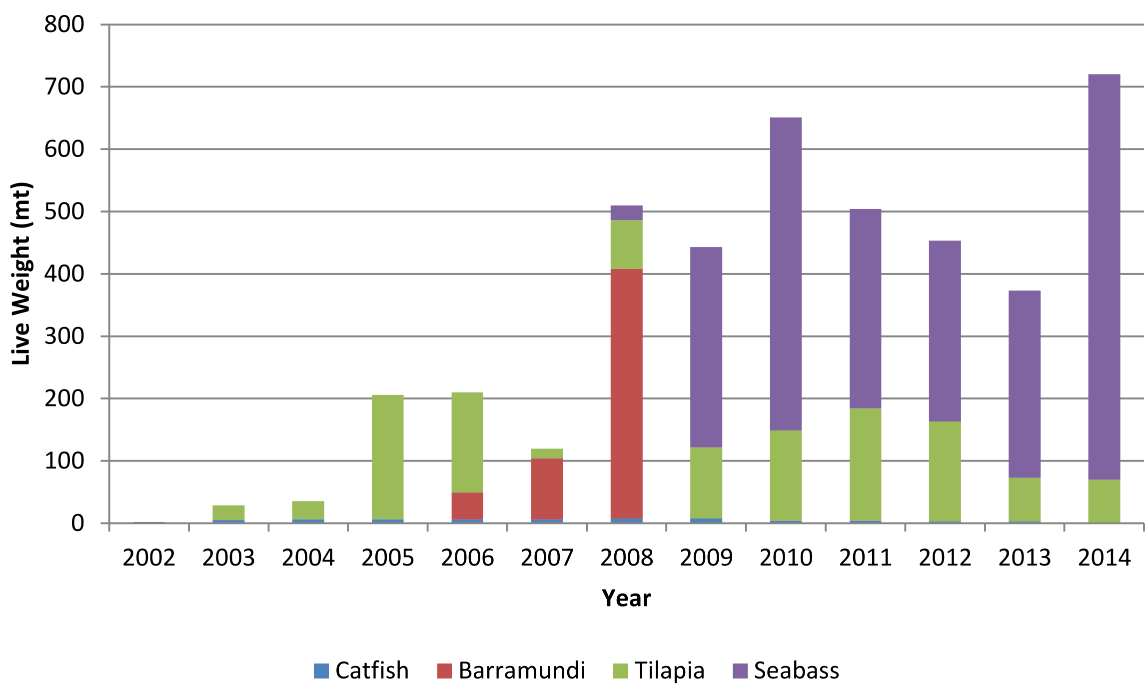
Figure 1: Number of UK RAS farms for table-fish production 2002-2013 (adapted from Jeffries et al 2010)



Of a total 29 RAS farms registered for grow-out production (i.e. excluding hatchery and smolt production) between 2000-2013, 18 (62%) were designed for tilapia production and most were UK Tilapia franchisees (Fig 1). The first wave of seven adopters (2005-2006) ceased production within 2-3 years (under-reporting in Figure 1 is due to delays in formal reporting of closures). However in most cases movable plant was 'recycled' by UK Tilapia and passed on to successive waves of adopters in the region; thus the total number of adopters over-estimates the amount of actual physical capital involved in this 'boom'. The progressive south to north axis of adoption along the English East coast suggests some degree of local communication and awareness of these problems. However, wider knowledge of the failures remained remarkably contained, perhaps reflecting the insularity of these farming communities as well as the aforementioned sensitivity regarding commercial failure.

Farmers also adopted a range of collective and individual strategies to bring the struggling businesses to profitability with varying degrees of success. This included investment in third-party or often self-implemented design improvements. One farmer acquired refrigerated transport for value-added micro-marketing of his produce and potentially that of neighbouring farms, though ultimately had to sell the bulk of his harvest to Billingsgate market where it competed directly in the mainly ethnic market for low-cost imported tilapia. Three of the later-adopters came up with the most enduring survival strategy forming the 'Fish Company'[4] to collectively market their product at the volumes and supply-regularity required by supermarkets; successfully contracting with Morrison's and with M&J Seafoods who supply the restaurant sector. The total design capacity of these farms was around 800t/yr most of this associated with one 500t farm, by far the largest of the 'boom'. Faced with the same problems as other franchisees, the owner of this farm took the decision to simultaneously re-design and significantly upscale the farm to produce more commercially realistic volumes for the supermarket trade. Experienced professional management (from outside the UK) was also brought in and steps taken to reduce production costs through energy-efficiencies through installation of solar panels and biomass heating systems - also reinforcing a sustainable marketing message. Despite these efforts, sales-volumes came nowhere near the anticipated levels (Fig. 2) leading to the recent closures of two of the Fish Company farms leaving only one of the smaller units still trading at the time of this report.

Figure 2: UK RAS table-fish production 2002-2014 (adapted from Jeffries et al, 2010)



Note: 2011-2013 data and 2014 projections based on survey responses.

[4]http://www.cookingtilapia.co.uk/http://aquaculturedirectory.co.uk/lincolnshire-home-to-sustainably-farmed-tilapia/

Parallels of this history can be observed in the demise of New Forest Barramundi which operated for just over two years between 2006 and 2008. Located in a converted pizza factory in Lymington, Hampshire the farm originally designed to produce 400t/yr for the UK market had a modular design intended to allow rapid expansion to an estimated 1,200t once markets were developed. Although farmed in freshwater barramundi (*Lates calcifer*) is a diadromous species also tolerant of brackish conditions. Due to its lack of bones, sweet-buttery taste and high Omega 3 fatty acid profile it is highly popular with consumers in its native Australia. Unlike tilapia, no alternative sources of imports were established; i.e. there were no direct substitutes. The challenge of marketing a novel-species remained, though it shares many qualities with farmed Mediterranean sea bass already firmly established in the UK market (barramundi is also known as Asian sea bass). Fortunately, owners London-based Aquabella Group who raised £6.86 million in equity (87%) and debt (13%) capital[5] over the life of the venture had considerable seafood marketing experience. They came to the market with firm contracts through trial sales already established with Morrisons and Waitrose; Sainsbury's, France's Intermarche and wholesalers M&J Seafoods, Daily Fish, Macro cash & carry and Costco were subsequently added. However, once again RAS production experience was lacking. An additional £4.58 million working capital raised on top of the original £2.28million investment was used for the remediation of design defects and to subsidise operational costs whilst the farm ran at significant under-capacity. Remediation included a new de-nitrification plant, improved sludge management processes and an ozone injection system all aimed at improving the quality of the fish –most seriously an 'off-flavour' taint associated with unfavourable biological activity in the system. Aquabella also planned to shift its original focus of selling whole fish to value-added gutted, filleted and smoked product. However, despite this considerable additional investment, it proved difficult to recover the confidence of buyers once tainted fish had reached the market. Their troubles were further compounded by the impact of low demand during winter months. Ultimately sales fell far short of original projections resulting in production costs more than twice the farm-gate price and post-tax losses of £2.64 million on revenues of £0.46 million in the second year.

Our third case-study is Anglesey Aquaculture[6] located near Penmon on Anglesey, Wales, and the only marine RAS currently producing table-fish (seabass; *Dicentrarchux labrax*) for the UK market. This one farm has contributed more than three quarters of all such production in every year since 2009 (Fig 2). The farm was developed by Selonda Aquaculture SA[7], based in Greece, using water treatment technology supplied by the specialist RAS engineering company IAT (International Aquaculture Technology) who had a proven track-record in the design and construction of intensive smolt RAS for Scottish salmon producers. Pilot trials with sea bass encouraged Selonada UK to commission a scaled-up RAS with a target production of 1,000t/yr. The farm produced its first fish (approx. 320t) in 2009. Financial difficulties of the parent company in Greece, linked to the international debt-crisis, were the predominant factor in the farm's underperformance and near closure in the following years. The company finally went into receivership in January 2012 with annual losses of £1.7 to £1.8 million on a turnover of £1.9 to £2 million in 2009-2010 (the last two years of operation for which accounts are available (FAME 2013)).

Tethys Ocean B.V., the aquaculture division of Linnaeus Capital partners B.V. (Linnaeus) immediately acquired the assets, renaming the company Anglesey Aquaculture Ltd (AAL). Past production output has varied between 300 and 500t (Fig 2). Following recent management changes the company predicts production will increase to between 600-650t in 2014 and aims to achieve full operational capacity in 2015. It is possible the company may then move into processing and value-added activities. No turnover figures are yet available for the first year of operation although it reported a liquidity ratio (liquid assets/short-term liabilities) of 0.56 (compared to a value of 0.11 for Selonda UK in 2010) and a QuiScore[8] (the likelihood of a company failure in

[5]http://www.proactiveinvestors.co.uk/companies/news/319/aquabella-is-struggling-with-barramundi-0319.html
[6]http://www.angleseyaquaculture.com/index
[7] With financing also from the Saudi Arabian Jazan Development Company (http://www.jazadco.com.sa/en/activity.htm)
[8]http://portal.solent.ac.uk/mobile/library/help/eresources/using-fame-database.aspx

the next twelve months) of 67 placing the company midway between normal and stable credit assessment bands (there are 5 bands: secure, stable, normal, unstable, and high risk). The AAL venture is clearly pioneering and has benefited from a longer incubation period than the other case-studies. In addition to its interests in major Mediterranean sea bass and sea bream cage aquaculture companies, Tethys Ocean B.V. also owns Israel-based company Grow Fish Anywhere[9] and expresses a strong belief in the future of land-based aquaculture. In the short-term at least, it therefore appears likely to be more committed and able to fund any on-going liabilities than investors in the previous tilapia and barramundi case-studies.

In several of the case studies the original RAS design required modification and (sometimes substantial) further investment in light of operational experience. This in turn points to the bespoke nature of most of these commissions and the corresponding lack of standardised installations with proven track-records in the UK. In the case of AAL, problems were largely due to management and weak financial investment by the original developers. However, even in instances where sufficient funding was available to address the design problems, market factors clearly represented a further major underlying challenge to the economic sustainability of these ventures especially the barramundi project where the products sent to market were deemed unpalatable. To a significant extent all the longer surviving ventures adopted similar market strategies targeting premium market sectors through promotion of sustainability traits variously associated with RAS production and the target-species (Table 2). AAL has reported on its improved growth rates and expects to achieve market size fish of 450g in 50-60% of the time taken by cage fish in Greece or Turkey where winter temperatures suppress production. With continued improvements in management and understanding of RAS technology operation the company is confident of further improvements in growth performance.

Many if not all these claims are entirely credible and consistent with growing pressure to buy and eat sustainable fish; however more problematical from an economic standpoint is the size of such premium market sectors going forward and it's potential for saturation should RAS production, or that of sustainable capture substitutes, increase significantly. For example tilapias were promoted as a sustainable alternative to cod but sustainably-certified cod (and pollack) harvests have since increased considerably. Although some top-end restaurants have stocked tilapia the availability of low-cost imports also creates particular challenges in positioning this species as a premium option. The largest existing demand comes from the ethnic market which tend to 'buy on price' and are happy with cheap frozen imports typically also of larger individual size. As indicated earlier the (limited) success of tilapia RAS in North America is associated with a sizeable niche ethnic market for higher value live-fish sales.

Whilst sea bass (and sea bream) already tend to occupy a more premium niche they are also challenged by the scale of Mediterranean production. Despite apparent sustainability contradictions linked to localness and air-miles, Anglesey Aquaculture is targeting a much larger USA premium market as a key plank in its expansion strategy. They have commenced regular air-freight deliveries to US-based 'Whole Foods Market' which brands itself as 'the world's leading retailer of natural and organic foods' with a global network of 340 stores (including 7 in the UK); the majority of seafood consumed in the U.S. is in restaurants. To this end, Anglesey Aquaculture has also invested in achieving the 'responsibly farmed' seafood standard developed by Whole Foods Market and required of their seafood suppliers. The Dansish Langsand Laks salmon RAS venture (section 4.2) is also undergoing assessment against the same standard (as well as ASC certification) and seeking evaluation by the Monterey Bay Aquarium Seafood Watch program[10], suggesting that it is also targeting the same USA segment as part of its marketing strategy.

However reliance on overseas markets, particularly for fresh product with high transport costs also brings the risk of competition from local RAS start-ups, particularly for premium market segments. In fact the Whole

[9] www.GrowFishAnywhere.com
[10] http://www.langsandlaks.dk/

Foods Market contract with Anglesey Aquaculture coincides with the failure of Local Ocean (Hudson, Lake Michigan, 2009-2013) a prior supplier of saltwater-RAS marine fish to the company (sea bream, sea bass, flounder and yellowtail)[11]. A patent lawsuit brought against the company by Tethys Ocean's Israeli subsidiary Grow Fish Anywhere contributed to Local Ocean financial difficulties. As with other highly capitalised start-ups ($13 million was invested in Local Ocean along with substantial government support) there is a strong possibility that the business will see further 'reincarnations' (e.g. processor Atlantic Cape Fisheries is considering conversion to freshwater production)[12]. Assuming progressive standardisation of technology and product quality in a maturing and economically viable RAS sector, there would also be decreasing scope to differentiate similar species from different national RAS sectors other than by geographical indication. All three UK case studies cited in this section do promote their regional location in their marketing mix (Table 2.) particular the sea bass and barramundi farms sited in idyllic protected areas. This could potentially be formalised as a protected geographical indication (TGI), but it is questionable whether this attribute alone would secure a significant premium.

Table 2: Environmental and other quality product differentiation claims used by RAS producers to target premium ethical markets

Marketing claims/ Unique Selling Points (USPs)	**The Fish Company[13] (tilapia)**	**New Forrest Barramundi[14]**	**Anglesey Aquaculture[15] (sea bass)**
Environmental			
High water re-use rates		Y	Y
Energy minimisation/ recycling	Y	Y	Y
Carbon neutrality/ reduced emission		Y	
Composting/ recycling of farm waste		Y	Y
Use of 'sustainably sourced' feeds	Y	Y	Y
No negative impact on wild fisheries	Y		Y
Disease biosecurity (& no antibiotics)	Y		Y
Food safety and quality			Y
Use of hormone and GM free feeds	Y		Y
Product traceability	Y		Y
Highly fresh/ local & never frozen	Y		Y
Low food miles	Y	Y	Y
Year round availability	Y		
Improved taste over same imported fish			Y
Farmed species USP claims			
Minerals	P, Se, Vit B12		
Fats	High omega 3&6	High omega 3 [2]	High omega 3 [2]

[11]http://www.timesunion.com/business/article/Fish-gone-at-shuttered-Local-Ocean-farm-4863291.php
http://www.timesunion.com/business/article/Fish-in-this-story-didn-t-get-away-4746595.php
http://www.localoceans.com/
[12]http://www.undercurrentnews.com/2013/09/26/group-in-talks-to-buy-us-based-zero-discharge-saltwater-fish-farm/
[13]http://aquaculturedirectory.co.uk/lincolnshire-home-to-sustainably-farmed-tilapia/#sthash.HvhjVvV5.dpuf
http://www.cookingtilapia.co.uk/press-releases/Why_British_Tilapia_Makes_Sustainable_Sense.pdf
[14]http://www.grocerytrader.co.uk/News/March_2008/G_aquabella.html
[15]http://www.angleseyaquaculture.com/sustainability
http://www.fish2fork.com/en-GB/news-index/2013/Fish-farm-overcomes-Greek-tragedy-to-produce-sustainable-sea-bass.aspx
http://www.fishupdate.com/news/archivestory.php/aid/19684/Welsh_fish_farm_92s_green_credentials_are__perfect_fit_94_for_grocery_chain.html

Marketing claims/ Unique Selling Points (USPs)	The Fish Company[13] (tilapia)	New Forrest Barramundi[14]	Anglesey Aquaculture[15] (sea bass)
	'low in fats' [1]		
Net protein producer	Y		
Third party certification			
Organic		Planned	
Animal welfare	Claim	Planned	
MCS sustainable fish guide	Y (1 rating)		Y (1 rating)
Whole Foods 'Responsibly farmed'			Y
'Exclusivity' testimonials			
High end supermarkets		Y	Y
High end restaurants		Y	Y
High end fishmongers	Y		
Geographical indication	Y	Y	Y

[1]Such claims are somewhat misleading as the ratio of PUFA's to saturated fatty-acids in tilapia is relatively low – however total fat levels are also low making tilapia a lean protein source.
[2] Feed composition can also have a significant effect on fatty-acid profiles.

2.3 Other regional commercial RAS Examples

In this section we consider table-fish RAS grow-out ventures outwith the UK and the innovations that have conferred longer-term economic success. Recent salmon start-ups are considered in detail in section 4.2.

Headquartered in Helmond, Holland, Fishion BV[16] was established around 2003 as a Joint Venture between ZonAquafarming BV and Anova Food BV[17], later becoming part the aquaculture division of Dutch agricultural company the Van Rijsingen Groep. Fishion is the trade name of a supply chain from feed supply, farmers and processors to point of retail (as Anova branded products). Alliance partners co-ordinate production to closely meet market requirements e.g. feed management and quality assurance are adjusted in real-time through monitoring and telemetry systems installed along the value-chain. The company's antecedents began RAS production in 1985 successively producing a range of species including eel, sturgeon, salmon, tilapia and catfish. Fishion initially concentrated on tilapia production until around 8 years ago when focus began to shift to a hybrid catfish variety branded as Claresse[18] (a cross between two African catfish species: *Heterobranchus longifilis* and *Clarias gariepinus*). Pure *C. gariepinus* has been farmed for over 30 years in Holland, being widely adopted as a diversification strategy by intensive feed-lot pig farmers in response to increasingly strict environmental controls on nitrate-discharge from slurry-wastes. The already low farm-gate price of *C. gariepinus* subsequently collapsed due to over-supply. The Claresse hybridisation created advantageous production and post-harvest value-addition attributes including firm fillet texture, low bone content and most importantly white-pinkish colouration. The latter attribute was particularly important in differentiating Claresse from *C. gariepinus* which can yield a lower-value yellowish grey fillet. A further economic attraction lay in the ability to farm catfish at extremely high stocking densities (>300 kg/m^3) over a short grow-out period (from 15g to 1400g in 7 months); far more favourable than the optimum level of 80kg/m^3 achievable for comparably priced tilapia in the same RAS systems.

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[16]http://www.fishion-aquaculture.com/en/fishion/
http://www.ngva.org/data/Fishion%20-%20The%20Way%20Forward.pdf
[17]http://www.anovaseafood.com/page.asp?lStrLang=EN
[18]http://claresse.eu/en/about.htm

Factors contributing to the businesses longevity include efficient and proven RAS design, the range of experience and skills in the company and its business model. The directors included aquaculture graduates with a broad technical and business knowledge. Production comes from a small number of nearby family based-farms in Brabant – each requiring an investment of around Euro 2.5 million. The production systems which can accommodate catfish or tilapia with little modification were designed and built in cooperation with Danish company Inter Aqua[19] with a track record in RAS engineering. Considerable attention was given to mitigation of off-flavour problems in the design phase (e.g. elimination of anoxic 'dead-spots' that could support problem bacteria) as well as husbandry and harvest requirements e.g. transport trailers with integral weighing mechanisms can directly access bays between culture and harvest transfer raceways. To meet environmental discharge limits, the farms also include de-nitrification systems developed in collaboration with Wageningen University. This also results in extremely high recirculation levels and associated energy efficiencies; there is no requirement for water heating to an outdoor temperature of 0° C.

Previous research with tilapia RAS adopters in the UK (Young et al. 2010) clearly demonstrated very few adopters, especially small-scale farmers had the necessary mix of production and marketing skills required to effectively target premium markets. Fishion farms through a franchise deal similar in concept to that offered by UK tilapia, are clearly offering a credible combination of technical, fish-health and marketing support. This example demonstrates that the franchise model can offer a sustainable route to adoption with the production-orientation of small-family farms becoming a virtue in their cooperative alliance. The company provides the farms with feed and 12-15g catfish juveniles originating from breeding subsidiary Zon Aquafarming BV. The company ultimately aims to use a 100% vegetarian diet; though around 30% and 18% of the total feed currently used for catfish and tilapia grow-out respectively is fishmeal and fish oil (supplied by Nutreco and Copens).

Processing is undertaken by Fishion affiliate Claresse Visverwerking BV. Stock is processed entirely in response to confirmed demand (i.e. there is no storage on location) predominantly for distribution as chilled products in modified atmosphere (MAP) packaging. The introduction of this processing-step corresponds with a progressive shift from only 27% of production being destined for filleting in 2005 to 91% in 2009 on weekly harvests of 11t and 86t Live Weight Equivalent (LWE) respectively (the balance being sold as whole round product). Fishion distribution partner the ANOVA seafood group have a track record in product innovation and have taken a key role in positioning and promoting the Claresse brand. The company also uses many of the sustainability characteristics listed in Table 2 to differentiate their product - particularly from Vietnamese Pangasius catfish the main low-cost imported (frozen) fillet substitute for their chilled product.

High production efficiencies (Table 3) also means the company can profitably sell to lower-price market segments including institutional canteens as part of its market-mix. Figure 3 shows how continuous technical innovation progressively reduced unit costs for tilapia production (catfish data not available) against a background of increasing energy and feed-input costs. Of particular note are the relatively high levels of inefficiency during the first 8-9 years of operation (major gains followed in labour productivity, feed conversion and energy efficiency, juvenile and financing costs). Secondly the high contribution of feed costs which will also increase as a percentage of operational costs with increasing farm-scale, points to the need for engineering of feeds designed to optimise Feed Conversion Ratio (FCR) in RAS (Section 3.5.1). Labour (not shown) and energy costs - which will also exhibit positive economies of scale with increasing production capacity – fell to only 5% and 23% of operational costs respectively in 2010. Increasing costs and poor energy efficiency was a significant factor contributing to the failure of the recent UK tilapia start-ups.

[19] http://www.interaqua.dk/ras_plants.php

Table 3: Comparison of production efficiency factors for catfish, tilapia and salmon in RAS

Company	Langsand Laks[20]	Fishion	Fishion	Traditional RAS'[1]	Open Aquaculture
Species	Atlantic salmon	Hybrid African catfish	Tilapia	Tilapia	Various
Culture medium	Salt water	Fresh water	Fresh water	Fresh water	SW & FW
Grow-out weight range (kg)	0.125 to 4.5	0.12 to 1.4	0.12 to 0.8	0.12 to 0.8	Various
Grow-out time (months)		7 to 8	6 to 7	6 to 7	
Annual farm production capacity (live-weight t)	1,000[3]	1600	600		
Capital Investment (€ mill)	4.07[4]	2.5	2.5		
Max Biomass Density (kg/m^3)	85-100	>300	80		
Energy efficiency (kwh/kg)[2]	1.3 to 2.11	0.8	2 to 2.5		
Main pumps	0.97				
Other system pumps etc	0.25				
Cooling, denitrification, light, ventilation and other	0.89				
Water efficiency (l/kg)	250	20	25	300 to 500	3,000 to 30,000
Economic feed conversion efficiency	1.05 to 1.4	<1	<1		
Production cost (€/kg LWE)	3.1		1.4		

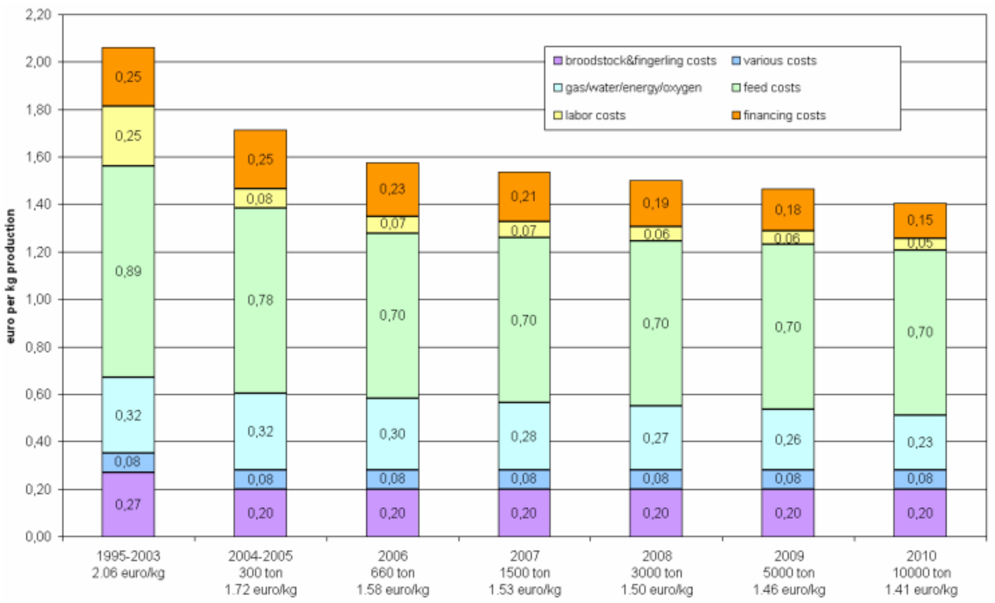
[1]Tilapia RAS without de-nitrification

[2] The energy efficiency of most industrial capture fisheries is typically >2.5 kwh/kg

[3]700t production forecast in 2014

[4] $3.5 million private investment and $2million Government grant

Figure 3: Cost price development of Fishion 600t tilapia farming systems (whole round ex farm)



[20]http://tidescanada.org/wp-content/uploads/files/salmon/workshop-may-2012/D1-4_Atlantic_Sapphire_%E2%80%93_1000_ton_Salmon_Production_in_Denmark_%E2%80%93_Langsand_Laks.pdf

3 RAS technology and range of application

3.1 Rationale for RAS

RAS technology has been introduced to the aquaculture sector to enhance environmental control of land based operations, increase security of marine and freshwater hatcheries and more recently for the ongrowing of seafood species to market size. The application of the technology to the latter sector is still in a state of rapid evolution for a range of vertebrate and invertebrate species – freshwater and marine. RAS technology for fattening farms does have several advantages as well as significant challenges:

3.1.1 RAS Advantages

- Longer average life of tanks and equipment (versus nets, boats) allowing for longer amortisation periods. However, serious attention needs to be applied to building infrastructure for marine species due to highly corrosive atmosphere that ensues when trying to maintain optimum temperatures in a temperate / northern climate.
- Reduced dependency on antibiotics and therapeutants generate marketing advantage of high quality 'safe' seafood.
- Reduction of direct operational costs associated with feed, predator control and parasites.
- Potentially eliminate release of parasites to recipient waters.
- Risk reduction due to climatic factors, disease and parasite impacts provided the RAS design has fully taken into account local climate, ambient air / water temperature conditions, incoming water treatment and bio-security.
- Head-starting species like salmon where it could be beneficial to lengthen the amount of time young salmon are raised in RAS before being transferred to cages. This reduces the amount of time the fish are exposed to the risks of the ocean growing environment, as well as potentially reducing total production times by optimizing the growing conditions.
- RAS production can promote versatility in terms of location for farming, proximity to market and construction on brown-field sites. However, they still need to be in close proximity to source water supplies and consideration needs to be given to local water quality and aesthetics since RAS farms resemble industrial buildings.
- Enable production of a broad range of species irrespective of temperature requirements provided costs of temperature control beyond ambient are energy efficient.
- Enable secure production of non-endemic species.
- Feed management is potentially greatly enhanced in RAS when feeding can be closely monitored over 24h periods. The stable environment promotes consistent growth rates throughout the production cycle to market size – provided the operator and RAS design has taken into account the diverse range of water quality management issues. Optimum environmental conditions promote excellent FCRs with some high value marine species achieving market size in 50% of time taken in sea cages.
- The advantages of RAS in terms of feed management assumes the operator has the capability to accurately control and record fish biomass, mortality rates and movements across the farm. Efficiency in these tasks becomes increasingly important with increasing farm size.

- Due to increased growth rates and superior FCRs that can be secured in RAS farms energy savings related to feed use may partially compensate for increased energy costs associated with pumping and water purification.
- Exposure of stock to stress on RAS farms can be reduced for some factors such as adverse weather, unfavourable temperature conditions, pollution incidents and predation. However, fish welfare can be reduced and exposure to stressful situations increased in relation to stocking density, chronic exposure to poor water quality and associated metabolic by-products due to inadequate water treatment technology or inexperienced management.
- In the UK, economies of RAS farm size are important and the technology tends to favour higher value seafood species rather than commodity species. This is a reflection of the relatively high labour and energy costs in the UK. RAS operation allows full control over effluent waste, nutrient recycling into value added products with limited energy production being feasible. However, the carbon footprint generated by a closed containment facility drawing electricity, pumping in water, filtering waste, among other actions, is significant. The source of the electricity, for example, hydro-generated or coal-generated, would play a major factor in the perceived sustainability of RAS. That said, a full life-cycle analysis of both cage aquaculture production and land-based RAS is needed. Dr Andrew Wright (Quoted in Weston, 2013) notes that no accurate accounting has been done to measure the methane releases caused by the decomposition of the wastes that accumulate on the ocean floor beneath open net salmon farms.

3.1.2 Challenges of RAS technology

- Lack of suitably experienced RAS managers and operators. Former cage or hatchery managers are not necessarily sufficiently well qualified to operate commercial scale RAS fattening farms without minimum 6-10 months training on the job. Poor awareness in terms of the broad range of water quality variables that require 24h in-line monitoring – especially in marine RAS.
- While RAS farms enable operators to avoid any release of particulate solid or dissolved nutrient waste into recipient waters its questionable how many investors take this issue seriously or appreciate the costs of implementing waste management into the production programme.
- Investors in RAS technology, even those with aquaculture experience, generally know little about water quality control, sea water chemistry and waste management at the industrial scale. Equally, RAS technology suppliers often know little about aquaculture and / or have a weak biological background.
- Investors fail to prepare adequately when identifying an appropriate RAS technology package – hence the large number of commercial failures
- Conclusion about economic viability of a RAS project is often based on assumptions and variables related to expected market price, utilization of the waste stream, product quality, optimal and maximum densities achievable, energy costs and costs relating to depreciation and interest on loans. Some of these criteria are subject to change and where assumptions are based solely on small pilot or research projects then even greater caution is required.
- Production of species preferring warmer water (20-25°C) can be advantageous both from a growth rate standpoint but also in terms of energy conservation. Maintaining optimum water temperatures for species like sea bass or bream, as opposed to species like turbot or halibut, is likely to be less

energy demanding in the UK provided the farm buildings are properly insulated[21]. Alternatively, if reliable, consistent low cost methods of cooling can be assured then the options for farming a range of temperate and cold water species alongside higher value Mediterranean or even tropical species are broadened. Experienced technicians to work with these species will need to be recruited from abroad.

- Species selection for UK RAS production is a critical issue. Irrespective of sustainability arguments for RAS production, the farm still needs to make a profit. Production of a commodity species in RAS which has to compete with the same product either imported or farmed using a lower production cost method requires serious risk assessment. The development of commercial scale marine RAS in the UK has focussed on the higher value seafood species such as European sea bass. However, this production still has to compete with large volumes of low priced imported product from the Mediterranean even though the latter is of inferior quality and not necessarily farmed with the same degree of sustainability.

- Ironically, superior prices can be secured in overseas markets for UK RAS farmed sea bass which is counter to the argument of building RAS close to the domestic market. Once effective RAS production becomes more widely deployed then options for the export of UK RAS production becomes more restricted and large scale farms producing in excess of 400-500 tonnes per annum will struggle to secure a premium price in the UK market for their entire annual production unless they can dominate the market with volume production and diversified value added products.

- Dependency on securing a premium price for a RAS farmed product justified by sustainability criteria may not always hold true. This is particularly so in terms of energy demand, energy source and associated carbon footprint.

- Reducing operational costs of RAS farms through utilisation of farm waste for value added products is perfectly feasible but is often over-played by developers. RAS farm effluent takes the form of a mobile sludge and dissolved nutrient streams which can be readily recycled into value added products such as composts, micro-algae and polychaete worms. However, the argument that parallel production of polychaete worms in RAS farm waste would be sufficient to totally substitute fish meal in feeds for the farm requires very close scrutiny - even if the polychaetes were nutritionally adequate as fish meal substitutes. The management of RAS farm sludge is a very real issue which few developers seem to properly appreciate at the outset of the project.

- The utilisation of RAS farm waste for on-site energy production is also feasible and the potential contribution in trial studies indicates this approach could be useful (Mirzoyan et et al., 2008; 2010). However, the investment in anaerobic digesters and equipment for conversion of gases to usable energy needs to be carefully balanced against the potential savings in power consumption. EU research into the potential of RAS farm waste as an energy source is currently underway (BiFFio - FP7: Research for the benefit of SME-AG) but this programme is focussed on the contribution of RAS aquaculture waste to energy production off-site and in combination with the larger volumes of agricultural waste. This approach will not necessarily benefit the RAS farm as it may still incur costs to transport the waste off-site under license. Ideally, energy generation utilising RAS farm waste should be implemented on site and this option should become increasingly attractive with larger farm sizes.

[21] This is due to the heat produced within RAS which can be conserved for warmer water species, but will require cooling for cold water species

3.2 RAS typology and design considerations

The basic principle of RAS is to re-use water though the application of suitable treatment processes. There can be varying degrees of water reuse depending on the system design. A simple flow-through fish farm where a water supply is diverted through ponds or tanks and then discharged has no water re-use. If aeration or oxygenation is added to the ponds or tanks there is already some water re-use as more fish can be produced using the same water flow. However, recirculation implies treatment of some or all of the discharge water and returning this to the fish rearing system as shown in the figure below.

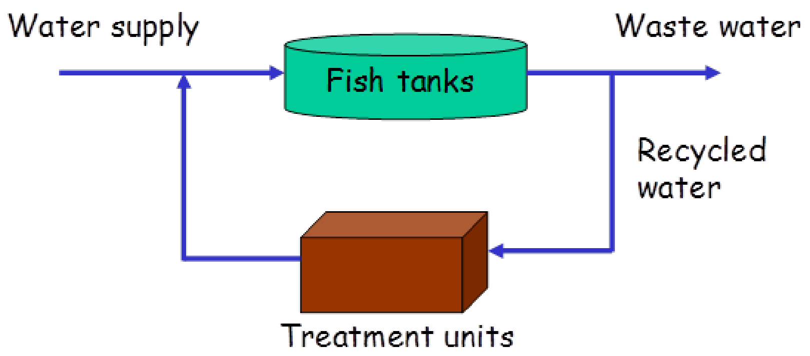


Figure 4: Basic concept of a recirculation system

Considering the above figure, a key design parameter is the ratio of recycled water to waste water (more commonly quoted as percentage of recycled water in the fish tank inflow water). A useful boost to farm productivity can be achieved by recycling say 50% of the water flow and using basic solids removal and re-aeration technology for treatment. As the ratio of recycled to new water increases, more sophisticated and efficient treatment processes are required with implications for capital and operating costs. If the drivers for using RAS include biosecurity, full control over environmental conditions or minimal nutrient discharge to nearby waters, then a high ratio of recirculated to replacement water is usually required (at least 95-99%).

A related measure of water re-use is the water replacement rate, which is usually quoted in percentage of the system volume changed per day. If for instance a system has a 95% recirculated flow at a rate that effectively replaces the full volume in the tanks once per hour; then over the course of 24 hours 1.2 times the volume of the tanks will be needed in new inflow water (120% replacement rate). A 5% per day replacement rate on the same system would translate to 99.8% of the tank discharge being treated and returned to the inflow. The inverse of water replacement rate is the water retention rate, so for a replacement rate of 5% per day, the retention of water within the system would be 95%. Somewhat confusingly, this is usually referred to as the "Percent Recycle" (Timmons et. al. 2001) particularly in North American literature. This makes rather more sense when the design of recirculated systems is considered, as very few employ a simple circuit as shown in Figure 4. In practice, few systems achieve greater than 98% recycle as water is lost from the system mainly through solids removal. Many experts in this area consider the term RAS to only apply to systems with greater than 90% recycle (less than 10% water replacement per day).

The essential functions of a RAS are:

- Provide a suitable physical environment for the fish with respect to space, water flow conditions, stock density
- Protect the stock from infection by disease agents
- Provide for the physiological needs of the fish (mainly oxygen and nutrition)
- Remove metabolic wastes from the fish (notably faeces, ammonia and carbon dioxide)
- Remove waste feed and breakdown products (solid and dissolved organic compounds)
- Maintain temperature and water chemistry parameters within acceptable limits

The latter target can be difficult to achieve in practice, as water quality parameters interact with each other in complex ways, especially in seawater. Furthermore, the operating conditions of the system are changing on an almost daily basis as fish grow, diets and feed rates change, and harvesting takes place.

The most common processes in RAS are shown in the diagram below.

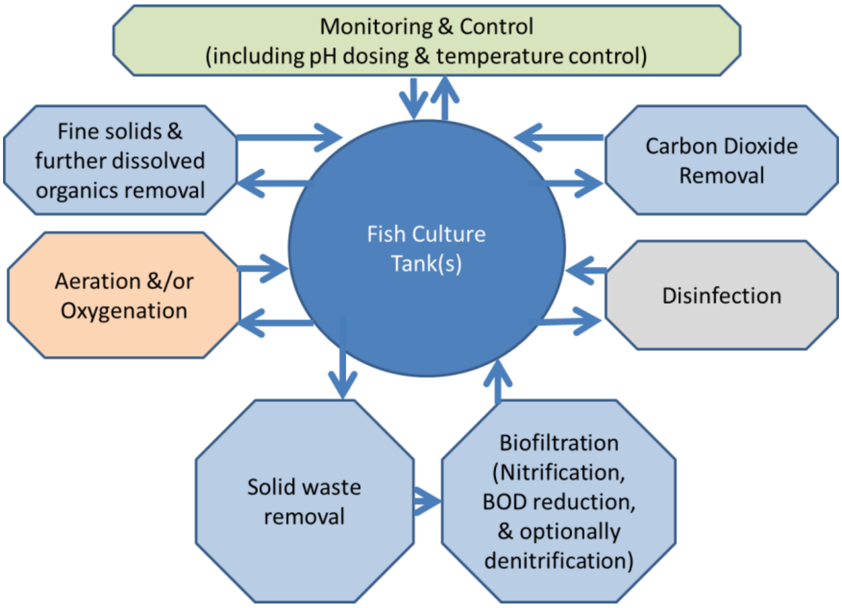


Figure 5: Common unit processes used in recirculating aquaculture production systems (adapted from Losordo et al, 1998)

Examples of technologies used in RAS are listed in Table 4

Table 4: Technologies used in high rate Recirculated Aquaculture Systems

Water quality factors to be controlled	**Example technologies employed**
Suspended solids	Sedimentation (for coarser particles) Self-cleaning screen filters Pressurised sand filters Bag and cartridge filters (for very fine solids) Foam fractionation (marine systems)
Ammonia	Biofiltration converts ammonia to nitrite and then nitrate.
Nitrate	Denitrification (or dilution in lower rate recycle systems with less sensitive stock)
Phosphate	Chemical precipitation or biological processes in combination with denitritfication
Dissolved organic compounds (mainly carbon)	Biofiltration Foam fractionation (marine systems) Ozonation
Carbon dioxide and nitrogen gas	Degassing – e.g. using vacuum degassers or forced air packed column trickle filters
Oxygen	Aeration at low saturation concentrations and oxygen injection at high saturation concentrations

Water quality factors to be controlled	Example technologies employed
Temperature	Heat exchangers with gas fired boilers or other appropriate heat source or chillers for cooling; Heat pumps
Pathogens	UV lamps Ozone (+ deozonation using activated carbon and/or UV)
pH	Chemical dosing (e.g. sodium bicarbonate); Calcium or magnesium compound filters; (Denitrification filters counteract alkalinity consumption)
Chlorine (e.g. if using a chlorinated supply)	Activated charcoal Degassing
Metals (e.g. iron, manganese in supply water)	Special absorption filters; Oxidation and/or chemical precipitation and filtration
Salinity	Adjust with freshwater or seawater addition

Modern RAS tend to employ multiple treatment loops as it may not be necessary to treat all the water on every cycle through the tanks and for some processes may be advantageous to prolong residence time in the equipment (e.g. ozonation). On the other hand, pre-treatment may be desirable for other processes, e.g. UV is more effective after fine suspended solids removal. Optimising the design with respect to minimising pumping costs and providing effective treatment and control can be a major challenge.

In most cases it will be necessary to use a separate water treatment system for incoming water and probably two or more separate systems for the farm itself. Whilst there are clearly scale related savings from using just one set of treatment equipment, this creates a greater risk of total loss if something should go wrong. It can also be desirable from the management perspective to have greater flexibility in operations and isolation between stocks. The major design parameters for RAS are shown in the table below.

Table 5: Major design parameters for RAS

Parameter	Comments
Salinity	This will depend on the requirements of the species, but marine systems have inherently more complex water chemistry and less efficient biofiltration. However, foam fractionation is a useful treatment only available in seawater.
Biomass & feed rate	These will generally be related, but the quantity of feed introduced to the system each day is generally the most important factor for system sizing. Further considerations are the variation in biomass and feed and in some circumstances, changes to the composition of the feed during the culture cycle
Stock density	This is highly dependent on species, size range and other factors such as water quality, tank dimensions and perhaps water flow dynamics. Higher stocking densities generally imply more efficient utilisation of tank volume and overall facilities
Production plan	The system is designed around the production plan which determines the expected length of time batches of fish will be in specific tanks, when they will be graded and moved to other tanks and when they will be harvested or moved out of the system. The use of multiple batches involving staggered stocking and harvesting schedules is normal in RAS to optimise use of resources and maintain reasonably stable biomass.
Water flow rates	These may be calculated in relation to biomass so as to provide a consistent replenishment of water per minute per kg or stock. However changes in

Parameter	Comments
	volumetric flow rate also normally changes water velocities, which can change other parameters such as solids removal and energy expenditure by the fish. Consideration of water velocities in relation to body length can be a useful design parameter.
Temperature control and energy efficiency	Maintaining optimum temperatures in RAS can be challenging, particularly where ambient temperatures vary seasonally, or are substantially different to the needs of the stock. The entire facility needs to be designed to minimise energy requirements for heating or cooling. Similarly, the energy required for pumping and gas exchange is probably the second major cost factor after feed and therefore careful design to minimise requirements and maximise efficiency is essential (e.g. through minimising pumping head, selecting wide bore pipes and efficient pumps etc).
Feed system	This will be specified based on volumes and feed rates required, the degree of automation and appropriate methods of (bulk) feed handling and storage.
Biosecurity	A risk assessment needs to be carried out that considers factors such as species, potential pathogens, disease susceptibility, location and potential routes of infection. This will lead to decisions on disinfection and other biosecurity measures.
Water quality targets	Target water quality criteria need to be set at the design stage to help define performance requirements for treatment equipment. Typical parameters include suspended solids, dissolved oxygen and carbon dioxide, ammonia, nitrite and nitrate, pH, alkalinity, salinity and temperature. Indicators of dissolved organic matter such as BOD and DOC or turbidity and colouration might also be set.
Monitoring & control	Requirements for system monitoring will be based on design the criteria and water quality targets set, together with a risk assessment of potential points of system failure. Computerised control systems can both help to reduce labour requirements and improve response to out of range conditions.
Fish movement and grading	Designs should ensure that basic fish husbandry operations such as stocking tanks, splitting and grading stocks, moving to different tanks, interim and final harvests, vaccination and disease treatments can all be performed as efficiently as possible. Fish pumps are commonly used, but there are implications for tank design and layout and building design. Consideration must also be given to the removal and management of mortalities
Waste treatment and disposal	The major waste stream from RAS is organic solids which frequently need dewatering and other treatment prior to disposal or utilisation elsewhere

3.3 Current examples

Some examples of recirculation configurations are shown below. These are taken from documents or websites made public by the manufacturers or researchers concerned. No endorsement of specific approaches or technologies is implied through the selection of examples.

The first example is a RAS for salmon smolt production marketed by the Norwegian company Akva (through a buy-out of the Danish firm Uni-Aqua). This features a double loop which treats the full recycled flow with solids filtration, UV disinfection and degassing, with only a proportion of the flow treated through moving bed bio-reactors (MBBR). Oxygenation is carried out at the tanks using cone injectors.

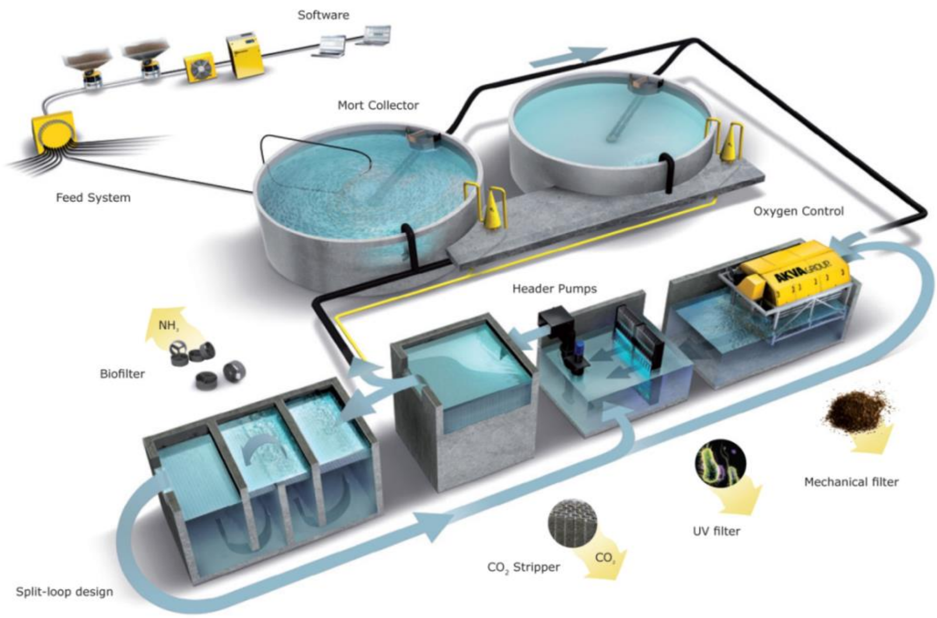
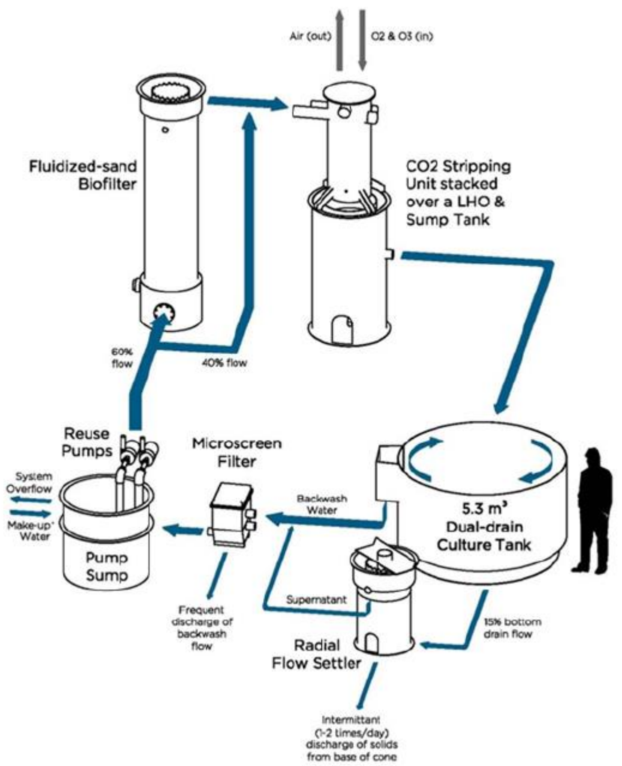


***Figure 6: Schematic of a modern RAS suitable for salmonids from AKVA*[22]**



A second and fairly similar example is taken from the Freshwater Institute in the USA, which has influenced many developments in recent years. It adds radial flow settlers to the solids removal process and uses fluidised sand biofilters rather than moving plastic media. As with the Akva system, a partial (60% flow) is passed through the biofilters.

Figure 7: Schematic of RAS design from the Freshwater Institute, Virginia USA*[23] *(experimental scale)

[22] http://www.akvagroup.com/products/land-based-aquaculture/recirculation-systems)

[23] http://0301.nccdn.net/1_5/2ec/317/07d/06-Summerfelt_Update-on-growout-trials.pdf

The third example is an experimental scale marine RAS designed at the Centre of Marine Biotechnology, University of Maryland, USA. The system components include: (A) 0.3 m^3 microscreen drum filter, (B) 0.4 m^3 pump reservoir, (C) 0.9 m^3 CO_2 stripper, (D) 1.5 m^3 protein skimmer, (E) 8 m^3 nitrifying moving bed bioreactor (MBB), (F) 1 m^3 low head oxygenator, (G) 0.6 m^3 pump reservoir, (H) 0.15 m^3 conical sludge collection tank, (I) 0.5 m^3 sludge digestion tank, (J) 3 m^3 denammox fixed-bed up-flow biofilter, (K) 0.02 m^3 biogas reactor with gas collection. Tank water was used to backwash organic solids from the microscreen drum filter (A).

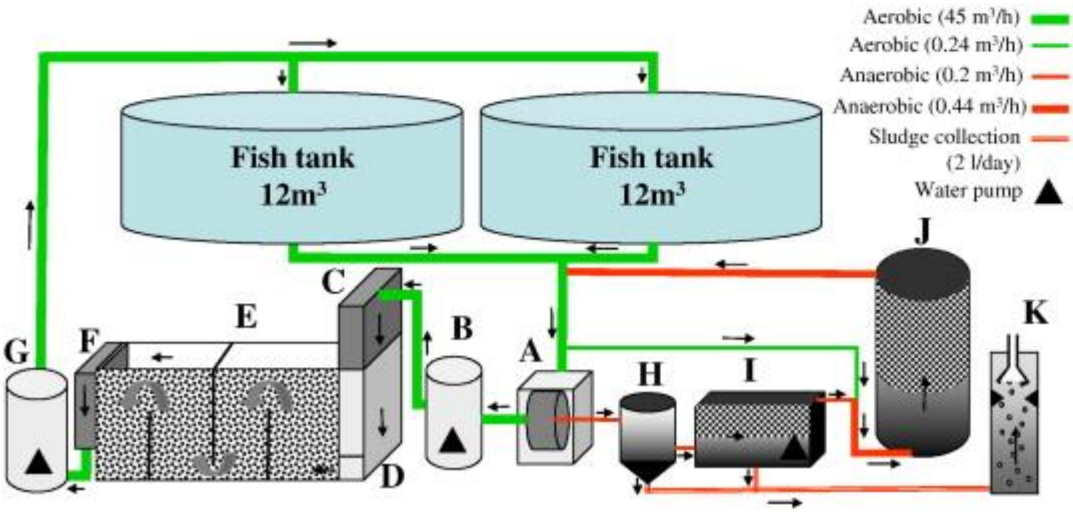


***Figure 8: Schematic of RAS design from the Centre of Marine Biotechnology, University of Maryland, USA*[24]**

A somewhat similar system is used by Aquatec-Solutions, a Danish RAS technology supplier:

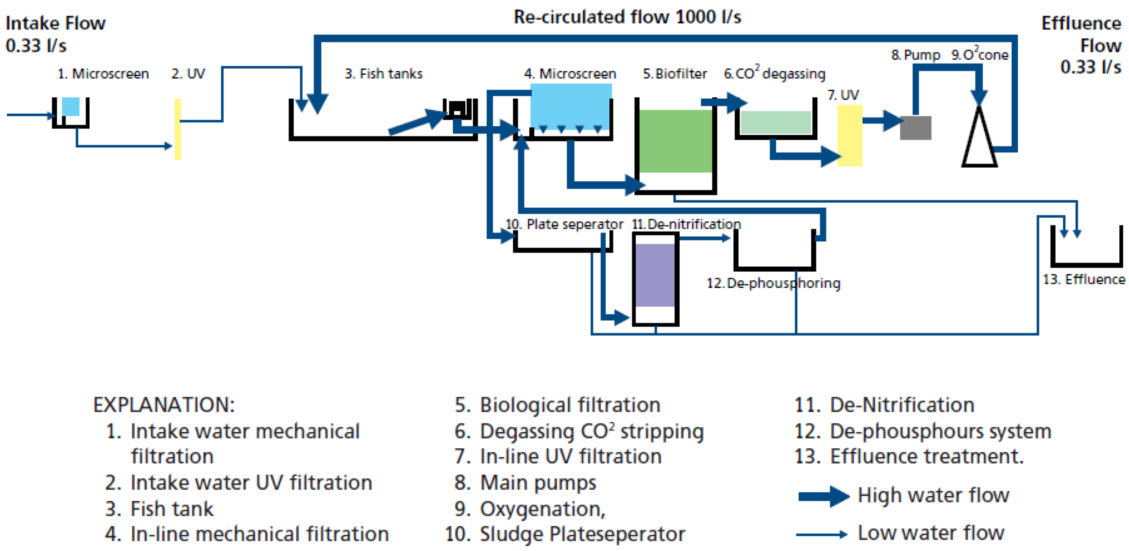


***Figure 9: Schematic of RAS design from Aquatec-solutions in Denmark*[25]**

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[24] http://www.interfishexpert.com/environmentally-sustainable-land-based-marine-aquaculture/

The inclusion of an anaerobic circuit complicates the design, but with potential benefits discussed below.

3.4 Biosecurity and disease issues in RAS

3.4.1 General issues and approaches to biosecurity

Public demand for reduced impact on the environment in an industry where the market for seafood continues to expand is pushing the aquaculture sector to develop new intensive technologies and approaches to traceable and sustainable seafood production. RAS are expected to reduce the incidence of disease outbreaks, lower dependency on medication and promote more stable production aimed at meeting the demands of the seafood market.

Biosecurity includes any company policy and procedures used on a farm that reduce the risk of pathogen introduction or spread through the facility if they are introduced. Delabbio et al. (2004) surveyed the trout sector in the US and showed that RAS biosecurity was not homogenous. Overall, inexpensive and low-tech biosecurity practices were utilized with the most common limited to record-keeping and dead fish collection. 66% of facilities reported prophylactic use of chemicals on fish while 81% reported therapeutic use. Quarantine procedures on incoming fish and/or eggs were commonly employed in RAS facilities, with use of an isolation area occurring more frequently (83%) than use of an isolated water supply (66%). These examples do not represent the type of RAS technology that is relevant to enhancing seafood production or diversification within the UK.

One of the primary advantages of RAS technology is that it provides the farmer with the opportunity to reduce disease outbreaks and actually eliminate some diseases altogether. However, while RAS can create optimum conditions for fish culture, inferior designs may inadvertently provide favorable conditions for disease outbreaks or the reproduction of opportunistic pathogens (Delabbio et al., 2004; Timmons et al., 2002). Where pathogens have already gained access to the RAS their potential impact on the stock can be influenced by the quality of the system design but equally importantly the knowledge and experience of the RAS manager. In RAS farms where the farmer has incomplete control over the ambient environmental conditions, such as trout RAS located outside with weak biosecurity or in non-insulated buildings, the RAS system is exposed to variable environmental conditions (variable temperature, ammonia removal rates) which leads to system instability, favouring disease outbreak.

d'Orbcastel et al. (2009a,b) evaluated RAS trout farms and one of their main conclusions was that the sedimentation system showed a good but highly variable removal efficiency (60±28%) such that the remaining suspended solids are circulated and degraded in the system. This results in sedimentation areas in other regions of the RAS and general water quality degradation. Equally, biofilter efficiency was also variable due to lack of temperature control. Any deterioration in nitrification due to excessive suspended solids material can lead directly to nitrite toxicity and mass mortality (Kroupova et al., 2008). Maintenance of stable environmental conditions for the fish to minimize stress conditions and related susceptibility to any disease organisms is paramount. Jørgensen et al. (2009) monitored parasite infections in several RAS trout farms in relation to a range of environmental parameters such as temperature, pH, nitrite and ammonia-concentrations, use of formalin, mortality and feed conversion ratio. They showed that the incidence and impact of disease outbreaks varied according to the stability of the system. Unstable RAS environments lead to sub-optimal conditions for maintaining stock health. The situation is not necessarily reflected by poorer growth and survival of the stock but the fish may show reduced condition indices. Good et al. (2009a) observed a

[25] http://www.aquatec-solutions.com

significant increase in splenic and skin lesions in trout exposed to a reduction in water quality in addition to variable plasma chloride, blood urea nitrogen and greater fin erosion. This situation predisposed the trout to disease outbreaks and underlined the frequent outbreaks of bacterial gill disease (BGD) noted in RAS trout farms with insufficient control over water quality (Good et al., 2009b).

Once established in RAS, disease organisms can recycle with the rearing water and, because of low dilution levels, pathogen infection rates can escalate. Once established in a RAS it can be extremely difficult to eradicate disease organisms and parasites. Unlike flow-through systems, traditional treatments for common trout diseases may simply not be practical in RAS due to the sensitivity of the important nitrification bacterial colonies in the biofilters (Schwartz et al., 2000).

Opportunistic fish pathogens may accumulate in the water column, biofilm and in the fish, encouraged by the prolonged water retention times, increased substrate concentrations, high fish densities, and continuous production techniques. As the pathogen concentration becomes amplified in the RAS, the risk of disease and epidemic loss increases. Obviously, strict biosecurity practices should be implemented to prevent introduction of fish pathogens from contaminated feed, water supply, fish and eggs from suppliers, and microbes carried into the fish culture facility by staff and visitors (Bebak-Williams et al., 2002). However, pathogens can access RAS farms via water vapour droplets particularly when farms are located close to source waters. If biosecurity barriers are breached and fish pathogens enter a fish farm, then the disease problem must be addressed through disinfection techniques that are costly, time consuming and do not necessarily lead to the elimination of the pathogen (Sharrer & Summerfelt, 2007). Once a parasite gains entry it must become part of the farm's overall management strategy alongside management of the biofilter bacterial populations and the farmed stock.

Husbandry practices that include regular tank cleaning and the flushing of sumps and pipes can reduce pathogen reservoirs and thereby decrease potential epizootic outbreaks (Bebak-Williams et al., 2002). Well designed RAS have a more stable microbial community structure with higher species diversity and a lower fraction of opportunists (Attramadal et al., 2012). Achieving this stable situation is largely dependent upon the efficient removal of suspended and dissolved solids. Any accumulation of nutrients and dissolved organics originating from uneaten feed and fish faeces can create an environment favorable to a diverse range of bacteria, protozoa, micrometazoa, dinoflagellates and fungi that can have a major impact on water quality (Moestrup et al., 2014; Blancheton, 2000; Leonard et al., 2002; Sugita et al., 2005; Michaud et al., 2006) and subsequently the stock.

The manner by which organic waste is processed and removed from the RAS is the area of greatest deliberation among RAS technology suppliers. Some recommend rapid removal through ozonated protein skimming while others prefer to mineralise the waste within the RAS, often using anaerobic, submerged moving bed bioreactors to assist with denitrification. This latter approach can have some benefits since reducing nitrate levels is also critical and cannot be controlled by dilution at high biomass levels. Certainly, the efficient use of ozonation technology can deliver good results but has been most successfully applied in the hatchery sector. Meanwhile, its application in high biomass on-grow facilities is much more of a challenge with very few aquaculture managers having had experience of its application and even then – only at the hatchery level. Installing or using ozone technology incorrectly has been the cause of several marine RAS failures in the UK and internationally. The issue with ozone technology remains the potential for introducing ozonated byproducts to the culture waters which can inflict subtle damage to the stock thereby reducing performance or under serious misuse situations cause direct mass fish kills. Only a few RAS technology suppliers include ozonation technology in their systems as significant expertise is needed to apply it at high biomass levels.

3.4.2 Parasites in RAS

Technology suppliers that claim their systems can never become contaminated with parasites are misleading the client. Even the most efficiently operated farms may eventually become contaminated by a range of monogenean, protozoan and dinoflagellate parasites. Both low and high tech RAS farms have become infected with pathogens irrespective of the level of control over water quality and despite biosecurity precautions. Equally, according to the design of the RAS farm and technology used, farms infected with parasites may still have the potential to infect recipient waters according to the manner or efficiency of farm effluent management.

In Europe, trout RAS farms have been contaminated with a vast range of parasitic organisms – some causing very significant mortalities. Even in Denmark, which pioneered trout RAS the importance of biosecurity has sometimes been overlooked. RAS infestations have included several ciliated protozoan species e.g. *Trichodina spp., Apiosoma sp., Ambiphrya sp., Epistylis sp., Chilodonella piscicola and Icthyobodo necator.* Other more complex parasites of trout include *Spironucleus salmonis* (Diplomonadida), *Gyrodactylus derjavinoides* (monogenean platyhelminthe) and the eye fluke *Displostomum spathaceum* (digenean). Jørgensen et al. (2009) reported that these parasites were introduced to the RAS farms by fingerlings supplied from traditional earth ponds. This point emphasizes the simple fact that it is a waste of investment to construct a RAS farm and then stock it with fry from an unrelated supplier or non-biosecure source.

RAS farms can offer a highly attractive environment for parasites and algal species that are directly parasitic or have toxic products that can be released to the culture waters. Some dinoflagellate parasites have the potential to bloom rapidly and cause catastrophic mortalities. Under these circumstances an efficient response needs to be implemented but the ability of any RAS farm to manage such outbreaks is dependent upon the quality of the farm design and RAS technology installed plus farm management experience.

Two recent cases in Denmark, involving rainbow trout and pike perch, were the first RAS farms in which serious dinoflagellate related fish kills have been reported in the EU although such parasites are known to kill up to 50% of stock in flow-through olive flounder farms in S Korea. In one Danish marine farm infested by *Luciella masanensis,* fish mortality increased dramatically despite treatment of the water with peracetic acid and chloramine-T. In another brackish water RAS farm infected by *Pfiesteria shumwayae,* the water was treated with chloramine-T, which caused the dinoflagellates to disappear temporarily from the water column, apparently forming temporary cysts. The treatment was repeated after a short period when the temporary cysts appeared to germinate and the dinoflagellates reappeared in the water column (Moestrup et al., 2014). UV was partially effective but both RAS farms closed. Very significant mass fish kills due to *Amyloodinium ocellatum* have also occurred recently in fully marine RAS farms but these have not been officially documented.

Despite the issues with parasites, experience with some commercial marine RAS farms has demonstrated a significantly lower incidence of some of the most common causes of mass mortality associated with culture of the same species in sea cages.

3.4.3 Harmful Algal Blooms (HABs) in RAS

While some HAB species may be directly parasitic other species can impact stock through toxins released within the RAS or indeed the source waters. HAB toxins are often grouped by the effects that they have on aquatic organisms. These include paralytic shellfish poisons (PSP), neurotoxic shellfish poisons (NSP), amnesic shellfish poisons (ASP), diarrhetic shellfish poisons (DSP), azaspiracid shellfish poisons (AZP), ciguatera fish poisons (CFP) and cyanobacteria toxin poisons (CTP). This diverse group includes neurotoxins, carcinogens and a number of other highly toxic compounds, many of which are well-characterized. The broad chemical and structural diversity of algal toxins coupled with differences in intrinsic potency and their susceptibility to biotransformation, account for many of the challenges associated with the detection of these compounds.

Technology capable of detecting HABs or toxic by-products would be a critical development for RAS holding high biomass loads at elevated stocking densities. Equally, secure raw water treatment prior to entering the RAS facility is a critical component of RAS design in farms exposed to potential HAB blooms.

3.4.4 Microbial pathogens

Bacteria, viruses and fungi are also significant potential pathogens and can be a particular problem in RAS that do not have good disinfection (UV and ozone). Bacteria that increase in numbers in recirculating systems include *Aeromonas spp*., *Vibrio spp*., *Mycobacterium spp*., *Streptococcus spp*., and *Flavobacterium spp*. (Yanong, 2009). Some UK tilapia producers suffered problems with *Fransicella asiatica* which were introduced through imported fry (Jeffery et al, 2011). Most microbes are reasonably susceptible to disinfection with UV, although some viruses such as IPNV require dose rates that are 7.5 times higher than most bacteria (Yoshimizu et al. 1986). The most effective defence against important viral disease is probably ensuring eggs, larvae or fry are sourced from specific pathogen free facilities and implementing strict biosecurity measures. Fungal disease has been a problem in freshwater systems, especially when fish are stressed or smolting. The use of up to 2 ppt salinity in addition to UV or ozone disinfection has been found to help minimise this problem.

Even the well managed farms can have a breakdown in biosecurity since many pathogens have the potential to spread by vapour droplets which are difficult to avoid where farms are located close to natural sources. In these situations the RAS farm is obliged to use therapeutants.

Despite these putative risks, empirical evidence suggests that in well-designed and managed RAS, outbreaks of pathogenic diseases and parasite infections have been mainly if not entirely due to the inadvertent transfer of infected fish. For example the bacterial pathogen responsible for a recent outbreak of Francisellosis in two tilapia farms (in the UK[26] and Belgium), was introduced with infected juveniles thought to have originated from SE Asia (this resulted in the culling of stock and full-disinfection of the farms). This was confirmed by a loss-adjuster for a prominent aquaculture insurance under-writer with over 12 years international experience of RAS ventures producing a wide range of fresh and saltwater species consulted as part of this report. He observed that mechanical failure and inadequate emergency back-up and alarm systems were the principle cause for concern. Disease problems on the other hand were very rare and in his experience 'due exclusively to transfers of infected fish' mainly associated with ecto-parasites such as *Ichthyobodo* or *Trichodina* spp,

3.4.5 Use of Chemical Therapeutants in RAS

When chemical therapeutants are added to RAS water the biofilters are often exposed to a high concentration of the chemical with a risk of impairing the nitrifying microbial population and hence reduce biofilter performance (Schwartz et al., 2000). Occasionally, it can be necessary to close the farm, disinfect and sterilize the entire production plant and start again. This is a hugely time consuming and expensive process which few farms will be able to survive – particularly for species with small profit margins. The ability to manage disease and reduce the risk of infection is therefore a critical component in the successful operation of RAS.

Chemicals remain an important tool to control fish pathogens in salmonid RAS (Jørgensen et al., 2009; Rintamaki-Kinnunen et al., 2005). For instance, high mortality caused by infections with the skin parasitic ciliated protozoan *Ichthyophthirius multifiliis* Fouquet, 1876 is a major problem in freshwater fish farming in most climatic zones (Heinecke & Buchmann, 2009) and is certainly a disease commonly encountered in the EU trout industry. *I. multifiliis* has a wide temperature tolerance (Aihua & Buchmann, 2001), a very low degree of host specificity and causes disease in wild and cultured freshwater fish (Dickerson, 2006). Infections with *I. multifiliis* cause extensive economic loss for both pond farmers as well as fish farmers using RAS technology

[26] http://www.int-res.com/articles/dao_oa/d091p161.pdf

(Jorgensen & Buchmann, 2008). Left untreated, infections can lead to high mortality in aquaculture production (Valtonen and Keranen, 1981). The parasite infects gills and skin surfaces of the fish and the life cycle comprises several morphologically distinct stages each fulfilling a discrete function in the life history of *I. multifiliis* (Lom & Dykova, 1992).

Originally, *I. multifiliis* disease was treated using malachite green but due to the carcinogenic and genotoxic potentials of this treatment (Srivastava et al., 2004) it has been prohibited for use in the production of consumer fish in the European Union by the council regulation (EEC) No. 2377/90 of the European Council. To control outbreaks of *I. multifiliis*, formaldehyde is most commonly used. It is an ideal chemical to add to RAS, having high treatment efficiency, harming neither the fish nor the biofilter at the concentrations used for treatment (Pedersen et al., 2007).

Formalin has been applied to marine (Keck & Blanc, 2002) and freshwater RAS (Schwartz et al., 2000), focusing on chemical measurements of the removal of ammonia and nitrite across the biofilter. Some of the studies showed significant impaired nitrification related to addition of the chemical. With formalin dosages above 100mg/L, it appears that nitrite-oxidizing bacteria were inhibited by the presence of formalin (Keck & Blanc, 2002). Pedersen et al. (2010) showed that nitrification rates were positively correlated to the amount and frequency of formalin treatment. In systems with regularly low formalin dosage, the formaldehyde removal rate increased up to tenfold from 0.19±0.05 to 1.81±0.13 mg/(Lh). Biofilter nitrification was not impaired in systems treated with formalin on a daily basis as compared to untreated systems. In systems intermittently treated with formalin, increased variation and minor reductions of ammonium and nitrite oxidation rates were observed.

Successful treatments typically include short-term repetitive topical baths with formalin at concentrations as high as 100 mg/L (Pedersen et al., 2010). This treatment regime has been shown to control the extent of infection, as formaldehyde (CH_2O; the active component in formalin) destroys the infective free living stage of *I. multifiliis* (Matthews, 2005). Formaldehyde is also effective against other ectoparasites such as the monogenean *Gyrodactylus* (Sortkjær et al., 2008; Heinecke & Buchmann, 2009). There is concern on potential environmental effects of excess formaldehyde discharge as well as worker safety issues. This has led to demands for a gradual phasing out of the chemical (Wooster et al., 2005). Despite research on more environmentally friendly chemicals, no valid substitutes for formalin have so far been implemented in RAS, partly due to insufficient treatment efficacy and the risk of biofilter collapse (Schwartz et al., 2000; Rintamaki-Kinnunen et al., 2005).

Hydrogen peroxide (HP) has been promoted as a substitute for formaldehyde and other chemicals to treat diseases and parasites in RAS and flow through systems. However, its use is not so well understood. It certainly has positive characteristics e.g. neutral byproducts, but it has been shown to have a significantly negative impact on biofilter operation – both moving bed and fixed media. The negative impact varies according to exposure time and level of HP used. However, it has also been shown to have very variable negative impact on biofilter operation according to the organic loading in the RAS. This is a critical point since RAS organic loadings can vary significantly according to system size, stocking levels, system volume, design (poor design = higher organic loadings), feed quality and a range of other environmental variables that may impact fish appetite (feed wasted) – and efficiency of feed metabolism.

3.4.6 Alternative Treatments

Use of UV in combination with ozone has proven commercial application in marine RAS. Similarly, in freshwater RAS, ozone and UV combined are effective in the management of pathogens (Summerfelt et al., 2009), but to date this approach is not commercially applied in full-scale open Danish RAS trout farms (Pedersen et al., 2009) possibly due to the additional investment costs required and lack of confidence in their application.

Peracetic acid (PAA) and hydrogen peroxide (HP) are powerful disinfectants with a wide spectrum of antimicrobial activity. PAA and HP degrade easily to oxygen and water and have potential to replace formalin in aquaculture applications to control fish pathogens. Low PAA additions (1.0 mg L^{-1}) caused only minor impaired nitrification, in contrast to PAA application of 2.0 and 3.0 mg L^{-1}, where nitrite levels were significantly increased over a prolonged period. PAA has good antimicrobial activity and antiparasitic effects over a wide temperature range, including temperatures below 10°C (Colgan & Gehr, 2001; Pedersen et al., 2013). It is relatively stable at low organic matter content, and it is degraded into water. PAA does not cause sublethal effects to the fish treated nor does it impair the nitrification process in the RAS biofilter at the dosages applied.

Heinecke & Buchmann (2009) describe a process for establishing a preventive strategy against *I. multifiliis* in fish farms involving filtration of free swimming stages (tomonts) so interrupting the parasite life cycle. When combined with the use of an environmentally neutral compound (sodium percarbonate, SPC) (releasing hydrogen peroxide) for eliminating the infective stages, the infection can be kept at an acceptable level. SPC was tested and compared to formaldehyde (FA) and was found to have higher efficacy compared to FA but temperature and concentration of the chemical had significant influences on parasite survival. For both chemicals negative correlations were seen between survival of theronts and exposure time, temperature and concentration. Micro-filtration studies demonstrated that it was possible to filter out 100% of the tomonts using a mesh size of 80μm.

The feasibility of filtering small parasitical stages from large volumes of circulating water to maintain the required removal rate might be a challenge. However, Heinecke & Buchmann (2009) did report that mechanical filters (drum filters with nylon mesh with pore sizes of 70 μm) were effective in Danish RAS trout farms which experienced severe white spot disease problems during the first two years of operation.

3.4.7 Non-chemical Control of Disease

Sharrer & Summerfelt (2007) promote the concept that trout RAS require an internal disinfection process to control population growth of pathogens and heterotrophic bacteria. Although disinfection of recycled process water adds to the fixed and variable costs of these systems, mitigation of potential disease occurrence has been reported with ozonation by itself (Ritar et al., 2006) or just with ultraviolet (UV) irradiation (Sharrer et al., 2005). Ozonation and ultraviolet (UV) irradiation are two technologies that have been used to treat relatively large aquaculture flows, including flows within freshwater RAS. Sharrer & Summerfelt (2007) evaluated the effectiveness of ozone application alone or followed by UV irradiation to reduce abundance of heterotrophic and total coliform bacteria in a water reuse system. Results showed that when only ozone was applied at dosages – defined by the product of the ozone concentration times the mean hydraulic residence time (Ct) – that ranged from 0.10 to 3.65 min mg/L, the total heterotrophic bacteria counts and total coliform bacteria counts in the water exiting the contact basin were reduced to 3–12 colony forming units per milliliter (cfu/mL) and 2–18 cfu/100 mL respectively. Bacteria inactivation appeared to be just as effective at the lowest ozone ct dosage (i.e., 0.1 mg/L ozone after a 1 min contact time) as at the highest ozone ct dosage (i.e., 0.2 mg/L ozone after a 16.6 min contact time). Sharrer & Summerfelt (2007) advise that RAS using UV alone provide a selection process that favours bacteria that embed within particulate matter or form bacterial aggregates that provides shielding from oxidation. However, when ozonation was followed by UV irradiation, the total heterotrophic bacteria counts and total coliform bacteria counts in the water exiting the UV irradiation unit were reduced to, respectively, 0–4 cfu/mL and 0–3 cfu/100mL. Consequently, combining ozone dosages of only 0.1–0.2 min mg/L with a UV irradiation dosage of approximately 50mJ/cm^2 would consistently reduce bacteria counts to near zero. These findings were orders of magnitude lower than the bacteria counts measured in the system when it was operated without disinfection or with UV irradiation alone. Their research shows that combining ozonation and UV irradiation can effectively disinfect recirculating water before it returns to the stocked tanks. No chemicals are released to the environment. However, ozone production does have a significant carbon footprint and if used incorrectly can be harmful to farm operators. Furthermore, to achieve stable RAS operation a stable bacterial flora in the production tanks is optimal.

3.5 Developing technologies

3.5.1 Diet density manipulation

Feeds used in most RAS are essentially the same commercial diets produced in high volume for cage or pond production systems, with minor or no adjustment. As solids separation is less of an issue in these systems other formulation goals are prioritised which (particularly in the case of salmon) result in nutrient-dense diets and what is effectively a perpetual state of diarrhoea in the fish consuming them. An alternative solution to the inherent problem of density-dependent solids separation and removal in RAS involves the engineering of denser RAS specific diets. For example this can be achieved through poorly digestible non-starch polysaccharides (NSP) to increase the integrity and specific gravity of faecal material e.g. substitution of wheat/ corn COH sources with barely oats. Legumes also have high NSP levels e.g. chickpea, broad beans, field peas which can be locally produced and are less susceptible to price fluctuations and environmental critique than soy inclusion (which has relatively high starch levels). Small quantities of NSP (i.e. 1%) have negligible impact on FCR though trade-offs will be incurred with increasing concentrations.

It might also be noted that the feed manufacturer Trouw, is marketing a specialised carrageenan based RAS diets intended to help prevent pellet breakdown and be a better binder for faecal particles. The diet is also designed to reduce phosphorus.

The EU funded 'Feed and Treat' [27] project (2012-2014) being undertaken by a consortium of researchers and industry partners (including Lakeland Smolt in the UK) aims to improve recirculation efficiency through a range of improvements in biological, mechanical filtration performance combined with feed optimisation. In addition to developing and testing a salmon smolt feed for RAS, the project will also produce design-criteria and a blueprint of future RAS and its commercial use.

3.5.2 Tank self-cleaning technology

Cleaning and disinfection of RAS tanks incurs significant labour costs but is essential for good fish health especially for juveniles. CLEANHATCH[28] is an EU funded project implemented by AQUABIOTECH Ltd, a Maltese SME has developed a retro-fittable ozone-based technology for reducing surface bacterial biofilms and residues. The designers claim significant reduction in labour costs and growth rate gains for a range of species including sea bream, sea bass, rainbow trout and turbot.

3.5.3 Nitrate denitrification in RAS

Nitrate toxicity

Several important publications have stated that NO_3-N is generally non-toxic to fish at concentrations that would be expected under typical culture conditions (Timmons et al, 2007; Colt, 2006). However, few specific studies have been conducted to evaluate the toxicity of NO_3-N to salmonids. Camargo et al. (2005) provided

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[27]EU (FP7-SME-2011-286143) http://documents.plant.wur.nl/imares/feedandtreat.pdf

[28]http://cordis.europa.eu/result/brief/rcn/11692_en.htmlhttp://www.cleanhatch.net

an overview of nitrate toxicity studies conducted with freshwater fish including salmonids. Several of these studies indicated that NO_3-N can be chronically toxic to salmonid eggs and larvae at concentrations <200 mg/L with sublethal effects occurring at <25 mg/L (Kincheloe et al., 1979; McGurk et al., 2006). However, establishment of acute, chronic, and sublethal NO_3-N levels depends upon life stage (Camargo et al., 2005). Westin (1974) reported a 96-hr LC50 NO_3-N/L of 1,364 mg NO_3-N/L for rainbow trout fingerlings. Despite the relatively high NO_3-N/L and a 7-day LC350 of 1,068mg NO_3-N/L levels reported for acute toxicity, Westin (1974) recommended a maximum allowable concentration of approximately 57mg NO_3-N/L for chronic exposure and only 5.7mg NO_3-N/L for optimal health and growth of salmonids. Several other studies have also concluded that NO_3-N concentrations could be a parameter of concern for various species cultured in RAS that are operated with low water exchange rates, including Martins et al. (2009) - common carp; Hamlin (2006) – Siberian sturgeon *Acipenserbaeri;* and Hrubec (1996) - hybrid striped bass *Moronesaxatilis x M. chrysops.* More recent studies are highlighting the toxicity of nitrate to both freshwater and marine species cultured in RAS (Schram et al., 2014; van Bussel et al., 2012) emphasising the need for its removal from RAS. Chronic nitrate toxicity can impair growth rates, impact tissue structure and gross body composition. In synergy with other chronic stressors it has the potential to increased susceptibility of stock to disease outbreaks.

Denitrification

In RAS trickling filter biofilms, denitrification activity was observed in distinct zones of the biofilm to a depth of 0.2–0.3 mm below the biofilm surface (Dalsgaard & Revsbech, 1992). Oxygen levels and organic matter availability dictated the depth of the denitrifying zone. Ammonia lowered nitrate assimilation rates and increased nitrate availability for denitrification (van Rijn et al., 2006). Oxidation of an organic carbon and electron donor and subsequent reduction of nitrate to elemental nitrogen yields around 70% of the energy gained with oxygen as the final electron acceptor (Payne, 1970). Under suitable conditions, high nitrate removal rates can be accomplished with this process. However, van Rijn et al. (2006) noted that information on denitrification in RAS is scarce and nitrate removal rates by denitrification reactors are reported in only a few studies. These authors note that volumetric nitrate removal rates in commercial farms vary significantly (1–166mg NO_3-N/l/h) most likely due to differences in system design, farm operation, types of electron donor, reduction states of the reactors, and the ambient nitrate concentrations at which the various reactors are operated.

In industrial wastewaters, the removal of nitrogen is generally performed using standard techniques of nitrification and denitrification processes. This procedure is suitable for the treatment of wastewaters with high content of ammonia and rich in biodegradable carbon because of its low cost and high efficiency as compared to physical and chemical treatment (van Dongen et al., 2001) but it is expensive for the treatment of aquaculture wastewaters with low carbon to nitrogen (C/N) ratios. The treatment of these effluents requires significant amounts of dissolved oxygen for nitrification and because the available carbon in some wastewaters is insufficient for the denitrification process, an external carbon source such as acetate, glucose, ethanol, methanol or methane gas must be added. These external carbon sources are expensive and can substantially increase fish production costs (Li et al., 2004; Noophan et al., 2008).

Denitrification in freshwater RAS

Studies on denitrification reactors in freshwater RAS were initiated in Germany by incorporating an activated sludge tank in the system for common carp (*Cyprinus carpio*) (Meske, 1976). Similar experimental systems with or without addition of external carbon sources were subsequently operated by a number of investigators with different freshwater fish species (Schmitz-Schlang & Moskwa, 1992; Knosche, 1994). Denitrifying activity in packed bed columns was studied by Abeysinghe et al. (1996) and Suzuki et al. (2003) with methanol as an external carbon source. Denitrification using endogenous carbon sources was studied in a closed freshwater RAS for tilapia (van Rijn & Barak, 1998; Shnel et al., 2002). In these studies, carbon compounds, released from the breakdown of endogenous carbon, were used to fuel denitrification in an anoxic treatment step consisting of a digestion basin and a fluidized bed reactor.

Denitrification in marine RAS
Gelfand et al., (2003) evaluated the feasibility of denitrification in a marine RAS comprising an anoxic digestion basin and fluidized bed reactor for culture of gilthead seabream with endogenous carbon as the sole carbon source. Nitrate removal in this system was mediated by both heterotrophic and autotrophic denitrification. Chemical analyses of the sulphur transformations and microbiological analyses of the bacterial populations in this treatment system revealed that sulphide, produced by sulphate reduction in the anaerobic parts of the digestion basin, was reoxidized by autotrophic denitrifiers (Cytryn et al., 2003). Alkalinity lost in the nitrifying treatment stage was fully regained in the anoxic treatment stage (Gelfand et al., 2003).

Additional evidence for the denitrification potential of nitrifying media was provided in a study on a moving bed bioreactor (MBBs) in a RAS for culture of gilthead seabream (*Sparus aurata*) (van Rijn et al., 2006). Zohar et al. (2005) and Morrison et al. (2004) reported innovative results demonstrating that the microbial consortia present in MMBs have the potential to support different nitrogen transformation processes that enable closing the nitrogen cycle and releasing nitrogen back to the atmosphere. Tal & Schreier (2004) combined an anaerobic digestion unit (ADU) with the main biofiltration system in a two-stage biofiltration approach tested in a pilot RAS in which adult seabream were grown at 40–50 kg/m^3 and fed daily at 1% of their body weight. This approach reduced 90–100% of the daily nitrate production of the nitrifying filter resulting in minimal nitrate accumulation in the RAS. During a 4-month experimental period daily water exchanges averaged as low as 1% of the tank volume significantly lower than the 7–10% achieved in earlier studies without denitrification.

3.5.4 Annamox systems

In the last decade microbial systems have been identified that bypass the formation of NO_3^- and convert NO_2^- to N_2 gas with NH_4^+ as the electron donor and NO_2^- as the electron acceptor under anaerobic conditions. The process is called ANaerobic AMMonium Oxidation or Anammox. Strous et al. (1997) reported that both pure and mixed ammonium oxidizing bacteria and Anammox bacteria under anaerobic conditions were able to use nitrite as an electron acceptor and ammonium as an electron donor. Tal et al., (2008) report on the development of a pilot land-based, marine RAS that is fully contained, claiming virtually no environmental impact as a result of highly efficient biological waste treatment and water recycling system. Over 99% of the water volume was recycled daily by integrating aerobic nitrification to eliminate toxic ammonia and, for the first time, simultaneous, anaerobic denitrification and Anammox, to convert ammonia and nitrate to nitrogen gas. Hydrogen sulphide generated by the separated endogenous organic solids was used as an electron source for nitrate reduction via autotrophic denitrification and the remaining organic solids were converted to methane and carbon dioxide. System viability was validated by growing gilthead seabream from 61 g to 412 g for a total production of 1.7 tons in just 131 days with 99% fish survival. Ammonia nitrite and nitrate did not exceed an average daily concentration of 0.8 mg/l, 0.2 mg/l and 150 mg/l, respectively. Food conversion values were 16% lower than recorded levels for net-pen aquaculture and saltwater usage of less than 16 l/every kg of fish produced. The system is claimed to be site-independent, biosecure, devoid of environmental contaminants and species independent.

Applying the Anammox technology
The development of Anammox bioreactors as the major nitrogen removal process in RAS would be advantageous due to the reduced oxygen demands and the autotrophic nature of the process, which allows complete nitrogen removal without a need for organic carbon. Savings in fish production costs would be made through reduced requirement for water buffering, lower oxygen costs, reduced pumping for water exchange and increased growth rates / survival. However, whether Anammox could be applied to commercial RAS as a means to control nitrogen load in lieu of conventional denitrification approaches remains to be determined. With Anammox bacterial numbers doubling times of around 11 days (Strous et al., 1999) the potential of these bacteria to replace conventional denitrification reactors is debateable and several researchers question their

potential application in RAS aquaculture (Tsushima et al., 2007). However, the successful application of Anammox in municipal wastewater treatment plants (Schmidt et al., 2003; Van der Star et al., 2007) suggests that further studies should be performed on the potential exploitation of this technology for aquaculture and to some extent this has been justified (Tal et al., 2008). A 2 year EU Framework programme developing Anammox technology has just been completed and an efficient bacterium was isolated and cultured in a prototype reactor supporting an experimental stocked sea bass RAS. This technology will now be further developed for commercial application.

3.5.5 Automated in-line water quality monitoring

The ability of RAS farmers to monitor water quality is generally limited to the essential parameters such as temperature, oxygen levels, pH, nitrite and ammonia and occasionally some heavy metals. However, other than temperature and oxygen levels most water quality parameters are monitored at spot points and at various intervals during the working day. As EU aquaculture production scales up towards greater intensification using RAS technology for hatcheries, head starting and fattening farms using lower water replacement volumes, there is a concomitant need for the farmer to be more aware of a much larger range of water pollutants derived from metabolic, bacterial and environmental sources. Furthermore, this data needs to be made continually (24h) available on-line.

While numerous sensors are available on the market to monitor individual water quality parameters no single instrument is available to provide multi-parameter analysis in real time and on a continual basis. This is a serious weakness for large RAS farms with a standing biomass in excess of 2-3 hundred tonnes. In such systems, the available reaction time (prior to stock loss / negative impact) due to a particular water quality parameter moving outside the optimum range may be measured in under 1 minute.

A current EU Framework 7 programme proposes miniature mass spectrometer (MMS) technology combined with orthogonal optical detection and is believed to be ideally suited to the measurement of multiple ion species down to parts per billion levels in RAS. The approach, allows real time, constant monitoring of potential toxins and substances that might taint or poison the fish, permitting corrective measures to be applied when a problem is detected. The system may offer near real time (minute-by-minute) on-line, detection of a wide range of substances but it can be reconfigured in software to "focus" on one part of the scan spectrum to provide high resolution (sensitivity and time) measurement of a specific substance of interest.

The wide utility of the MMS extends beyond measuring potentially harmful substances, but can also be applied to measuring substances that are more commonly measured – CO_2, nitrogenous compounds and methane. Importantly, the technology is capable of measuring these substances simultaneously and also offers an ideal route for direct measurement of methanogenesis in anaerobic digestion. Other applications pertinent to aquaculture include determination and monitoring the rates of Anammox and denitrification processes. Parameters that require new sensor technology for continual monitoring in RAS include tainting substances, hazardous algal blooms, hydrogen sulphide and a range of other gases:

3.5.6 Tainting substances: Geosmins (GSM) and 2-methylisorboneol (MIB) contamination of aquaculture water

Producers of GSM and MIB include *Streptomyces* species or cyanobacteria (Izaguirre and Taylor, 1995). *Streptomyces* species are also thought to be responsible for the synthesis and release of these compounds in RAS (Guttman and van Rijn, 2009; Schrader and Summerfelt, 2010). These products once released into the farm water are rapidly absorbed via the fish gills into the tissue fat conferring a distasteful 'muddy' flavour to the fish. In the US, off-flavour problems in pond-based systems for the culture of channel catfish have been estimated to cost producers as much as US$60 million annually (Tucker, 2000; Schrader et al., 2011). Catfish that are determined to be off-flavour must be held in ponds until flavour quality improves. It has been estimated that 30% of potential revenue is lost annually by the pond-raised catfish industry due to off-flavour problems because of delays in harvest that result in additional feed costs, forfeiture of income from foregone sales because producers are forced to delay restocking ponds, and loss of catfish during the holding period from disease, water quality deterioration, and bird depredation (Engle et al., 1995; Tucker, 2000; Smith et al., 2008).

The UK produces about 13,000 tonnes of trout, valued at £45 million using various production systems common throughout mainland Europe. During a survey of UK trout farmers as to the incidence of tainting issues 25% of the respondents surveyed stated that they had had problems associated with tainting, usually persisting for several weeks over the summer months. The costs to farmers, who are unable to sell fish while they are affected, can be conservatively estimated at many hundreds of thousands of pounds per annum and involve loss of sales, utilisation of valuable pond and tank space as well as additional feed and water costs. Farmers have no means of early detection of problems and thus must rely on reactive solutions once the compounds have been detected in the fish. The EU produced some 205 thousand tonnes of trout in 2007 valued at €539 million. On this basis the potential cost saving of an early warning system for taint compounds to EU trout farmers is very significant.

Several salmonid species such as rainbow trout (*Oncorhynchus mykiss*) and Arctic charr (*Salvelinus alpines*) raised in RAS have also been reported to possess earthy and musty off-flavors caused by GSM and MIB (Guttman and van Rijn, 2008; Schrader and Summerfelt, 2010; Schrader et al., 2010; Houle et al., 2011). Off-flavours have been reported to impact a number of other commercially important species, including Nile tilapia, *Oreochromis niloticus* (Yamprayoon & Noomhorn, 2000), shrimp (Whitfield et al.,1988), Atlantic salmon, *Salmo salar* (Farmer et al., 1995), rainbow trout, *Salmo gairdneri* (From & Horlyck, 1984), catfish species (Lovell et al., 1986; Martin et al., 1987) cultured largemouth bass, *Micropterus salmoides*, and white sturgeon, *Acipensertrans montanus* (Schrader et al., 2005; Smith et al., 2008). All these species are cultured within the EU using RAS technology ass attempts are made to diversify the species base for EU production, so will be exposed to taint issues if conditions are suited to the growth of organisms that release GSM and MIB. One UK Asian sea bass RAS farm failed in 2011 with significant financial losses due to GSM tainting of the flesh in products delivered to a UK multiple.

Purging fish of taints

The taint threshold i.e. the level below which the majority of people will not be able to detect a musty/earthy taint, is approximately 1 ppb (1 μg/kg). Once GSM and MIB are released in water they will rapidly accumulate in fish primarily entering via the gills. Laboratory experiments have demonstrated that GSM immediately begins to accumulate in trout when they are exposed to tainted water and reaches a maximum level in less than a day.

Taint is generally removed by depuration which can extend up to 15 days for salmonids. This is an inefficient and costly method in terms of managing the depuration process. Issues include the logistics of regularly depurating large volumes of fish, lost fish weight, reduced tissue fat content and condition factor. Neither is it a secure method due to the variable depuration response of individual fish according to their original taint and tissue fat levels. Purge times for salmonids were found to be directly related to initial taint concentration in fish of similar mass and fat content, held at the same temperature (14.5°C). Depuration times in all experimental groups were significantly increased when the time for a population of fish to purge clear was considered rather than the period required for the arithmetic mean concentration to reach sensory threshold limit (Robertson et al., 2005). Similarly, during depuration in pond raised channel catfish, the reduction of GSM and MIB levels to provide an “on-flavor” product can take days, weeks, or even months in some cases and depends upon a variety of factors including water temperature, adipose content of the flesh, and intensity of the initial off-flavor (Perkins & Schlenk, 1997; Dionigi et al., 2000; Burr et al., 2012).

As might be expected it is difficult to control tainting in open earthen ponds but in RAS farms its efficient detection and immediate removal should be feasible. Under laboratory conditions UV–TiO_2 photocatalysis has been demonstrated to cause a significant reduction of both 2-MIB and GSM using a packed bed reactor unit (Pestana et al., 2014). Detectable levels were reduced by up to 97% after a single pass through the unit. When the reactor was used to treat water in a fish farm where both compounds were being produced in situ a reduction of almost 90% in taint compounds was achieved. These very encouraging results demonstrate the potential of this UV–TiO_2 photocatalytic reactor for water treatment in fish rearing systems. This is a far more attractive proposition than the rather crude approach of determining depuration periods for RAS farmed salmon as proposed by Burr et al. (2012). A belief in depuration is a simplistic approach considering the investments involved with RAS and particularly when attempting to produce a quality product for sale at a *premium* price.

3.5.7 Efficient control of dissolved gases

Gases of interest - Hydrogen Sulphide, Methane, Oxygen, Carbon dioxide

In RAS, hydrogen sulphide (H_2S) is produced by bacteria in anoxic silts which can accumulate where tank design and pipe runs enable the settlement of faecal and feed waste. Hydrogen sulphide exists in two forms in the water, HS- (ionised sulphide ion) and H_2S (unionised hydrogen sulphide); the H_2S form is highly toxic to fish. In well oxygenated waters, sulphide is rapidly oxidised to sulphate. Gases also routinely monitored include oxygen and carbon dioxide. While these can generally be measured using inexpensive probes, the MMS technology can also measure these gases in solution, illustrating its wide utility as a universal sensor.

Enhanced gas exchange systems

There is a significant energy consumption associated with either transferring oxygen into the culture water or removing high levels of undesirable gas such as carbon dioxide, nitrogen, and if needed, chlorine. Efforts are therefore ongoing to develop more efficient transfer technologies. For instance the company Coldep Developpement in France have patented a vacuum airlift system that combines degassing with foam fractionation and low head water pumping, with claimed savings in energy cost. In the UK, Pearlmax[29] is aiming to exploit a micro-bubble technology developed at the University of Sheffield. This is able to reduce the bubble size produced in diffusers and claimed to increase aeration rates by three to four fold and reduce power inputs by 18%. This is most likely to be used in aerations and oxygenation systems, but could be applicable in some degassers or ozonation systems where a ten-fold reduction in power requirements is claimed. Another technology that is so far restricted to specialist uses but has potential for aquaculture is membrane gas transfer technology. These are often in the form of hollow fibres that are porous for the target gases. For a degasser, a bundle of fibres would be positioned in the water stream to be degassed. Each fibre would have a small vacuum applied such that gas is drawn from the water into the fibres for extraction. An oxygenation system would work in reverse through applying a slightly higher gas pressure within the fibre. The major advantage is high transfer efficiency with lower energy requirements than conventional bubble or agitation based techniques (Yoon, 2012). The same technology can also be used to increase the efficiency of biofltration and other water treatment processes (Martin & Nerenberg, 2012).

3.5.8 Use of GMOs

After more than two decades of research, protracted public consultation and evaluation of the food-safety and environmental impacts of AquaBounty's genetically modified (GM) 'AquAdvantage salmon' (AAS), it now

[29]www.perlemax.com

appears increasingly likely that America's Center for Veterinary Medicine, a sub-body of the FDA, will grant it pre-market approval; legalising the first commercial production of a transgenic animal anywhere in the world. The AAS Atlantic salmon includes an ocean pout 'antifreeze' and a chinook salmon growth-hormone gene. Atlantic salmon have evolved to reduce growth at lower water temperatures when prey organisms are likely to be in low supply. The pout gene effectively over-rides this response allowing the growth-gene of the faster-growing Chinook to confer accelerated growth even at low temperatures. Faster growth will also correspond with significant improvement in food conversion efficiency.

Aquabounty claim double the growth rate of normal Atlantic salmon for ASS (though their trial data indicates juveniles can reach a weight of 500g after only 250 days from first feeding compared to slightly over 400 days for normal Atlantic salmon[30] i.e. a 40% reduction in grow-out time).Verification of these claims still requires independent benchmark comparisons of ASS with the products of leading conventional selective breeding programmes under commercial RAS grow-out conditions (e.g. Aquacatch, Salmobreed or Landcatch natural selection). Rates of non-GM trait improvement are also being accelerated through increased use of genetic marker technology (e.g. X-select). Furthermore, extremely low genetic diversity associated with the very small ASS founder population (probably a single family) reduce the potential for future desirable selective-breeding gains for traits e.g. for post-harvest traits such as yield or fat content. The GMO (genetically modified organism) mode of action also suggests greatest growth will be achieved at lower temperatures; however water temperatures in RAS can be optimised to particular life-stages.

FDA rules require product labelling when there is a difference in nutritional value, composition, safety (allergenicity) or processability of a food compared with its traditional counterpart[31]. Aquabounty claim that only regulatory biological processes are influenced and its eating qualities thereby unaffected. i.e. AAS expresses Atlantic salmon protein making it 'biologically and chemically indistinguishable from Atlantic Salmon'. Nevertheless, Aquabounty have publically committed to voluntary labelling and accept labelling by exclusion (i.e. for non-GMO fish)[32], though it is not clear how far they would enforce such requirements on farmers growing their product under licence.

To prevent any possibility of interaction with wild stocks all production will also be engineered to be sterile females. However FDA licensing will restrict ASS production to physically contained land-based RAS. Similar licensing in Europe or Canada is highly unlikely, certainly in the medium term. Although American consumers are more accepting of plant-based GM foods than their European counterparts, it remains to be seen just how far this attitude will translate to transgenic salmon and the premium it is likely to capture compared non-GM salmon. Assuming ASS achieves FDA market approval, consumer acceptance is good and the grow-rate differentials claimed by Aquabounty are justified, there would then appear to be a substantial comparative advantage for ASS culture in RAS compared to imported cage-farmed produce. This is significant as some 97% of the 200,000t of salmon annually consumed in the USA is imported, much of it destined for a sizeable premium market segment (Section 2.3). Economic success in the USA and elsewhere may contribute longer-term attitude shifts in more GMO adverse markets. Consumer attitudes are already likely to be more flexible in SE Asia markets.

GMO ingredients (e.g. soy and corn) are already widely used in the formulation of aquatic diets. Although some RAS producers restrict use of GMO ingredients as part of their sustainable-marketing strategy, this does not fundamentally differentiate RAS from cage-production alternatives.

[30] http://www.aquabounty.com/documents/press/2010/AquaBounty%20Fact%20Sheet%20-%20Corfin.pdf
[31] "Food and Drugs" Title 21 U.S. Code. Pts. 343. 2007 ed.
[32] http://www.aquabounty.com/PressRoom/#l3

4 Prospects for salmon farming in RAS operations

4.1 Background

Two main drivers can be discerned for salmon farming using RAS. Firstly, since the advent of salmon farming in marine and freshwater cages, there has been a constant lobby of opposition from various interest groups; In particular the salmon angling community, but also wider environmental and conservation groups. The main issues raised against cage-based farming are:

- Farms create reservoirs for disease organisms, particularly sea lice, which could affect migrating wild salmon
- Escapees from fish farms could compete with wild salmon, especially for spawning habitat
- Escapees that breed with wild populations could dilute their genetic integrity
- Solid organic wastes from the farms cause degradation of the local benthic habitats
- Dissolved nutrient wastes from the farms could contribute to eutrophication and increased risk of algal blooms
- Chemical and pharmaceutical use by farms could have adverse effects on other organisms and the local ecology
- Farms attract predatory animals (especially seals and sea birds) which can then be adversely impacted by anti-predator measures adopted by farmers (e.g. deaths due to entanglement in anti-predator nets)
- The visual amenity and utility of ocean-spaces for other recreational and commercial uses can be adversely affected by cage-farming.

Campaigners against cage-based farming argue that salmon should be reared in contained systems that do not allow the kinds of environmental interactions outlined above (e.g. Ecoplan International Inc. (2008) or see statements from the Atlantic Salmon Trust[33]).

A separate and perhaps wider community concern is that fish farms detract from the natural scenic beauty of an area and hence reduce value with respect to potential income from tourists etc.

A more general concern raised against salmon aquaculture is its use of fishmeal and fish oil in compounded diets. As this is also an issue for RAS farms, it is not a major driver for RAS adoption.

The second major driver has been the potential advantages of RAS as outlined in the previous chapter. This could be summarised as the technology driver. Potential users are attracted by the promise of control and consistency and removal of dependence on wider environmental variables including disease, severe weather, or predators etc. For others, the engineering challenge of developing self-contained systems which minimise water use, control wastes and optimise production, is sufficient reason to engage with RAS farm development.

4.2 Current activity

Swift Aquaculture, in Agassiz, BC[34], is a family operated business that farms Pacific salmon in RAS. The farm raises coho salmon in freshwater tanks, and also operates as a multi-trophic aquaculture site, using the

[33] http://www.atlanticsalmontrust.org/blogs/close-containment-the-plot-thickens.html
[34] http://www.seafoodchoices.org/seafoodsummit/documents/Swift,Bruce.pdf

nutrient-rich water from the salmon tanks to grow watercress and wasabi, which in turn produces algae to feed crayfish. The coho salmon from this farm is currently sold to high-end restaurants in Vancouver. Plans exist to expand this site to a 1000 tonnes RAS operation.

Coho salmon are also raised by ***AquaSeed Corporation*** at their 100 tonnes land based RAS facility in Washington State, as well as through a franchise with ***Teton Fisheries*** at two 160 tonnes facilities in Montana. These coho are marketed under the brand "***SweetSpring Salmon***," which supplies ***Overwaitea Food Group*** supermarkets in British Columbia and Alberta. Both Montana franchisees, established in 2011 ceased production in 2013 due to lack of profitability[35] whilst SweetSpring reportedly made losses of $3.7m over the same period.

Despite the setback in Montana, investment in RAS farms for Coho is continuing with an announcement[36] from ***Holder Timmons Engineering*** and ***Aquacare (Aquatic Environment Inc.)*** that they are working on new projects in British Columbia, Missouri and on Vancouver Island. The rationale for selecting coho salmon was explained by John Holder at a meeting of the Canadian Parliament Fisheries and Oceans Committee meeting in 2011[37]. Coho can be reared from first feeding to 3 kg harvest weight in 12 months with greater flexibility in terms of year-round fry supply. This enables more efficient use of tanks and more regular harvesting than is currently possible with Atlantic salmon. Furthermore, although it is a more niche species, prices are higher per kg than for Atlantic salmon.

Danish Atlantic salmon farm ***Oceanus***, located at Langsand Laks, is the first commercial RAS operation destined to produce 1,000 metric tons per year of Atlantic salmon. Involving both fish farmers and scientists the farm has sent its first salmon to market in January 2014. It is a DKK 100 million ($18.1m) investment with the government contributing DKK 23.8m and DKK 1m from energy company ***Nord Energi***. The project involves seafood producer and distributor ***Aquapri***, smoking house ***Polar Salmon***, wild fish harvesters ***Sohn Invest*** and RAS technology suppliers including ***Billund Aquaculture***, who are cooperating on the project. The product is targeted at markets in Japan, the US and Russia. Under full production the plant is designed to harvest 45t of salmon each week. The facility recirculates 13,000 cubic meters of water an hour at a fish stocking density of 80 to 90kg/m^3.

Norwegian salmon farmer ***Atlantic Sapphire*** is also involved in ***Oceanus***, and is planning a similar venture in North America. It is also a partner in a proposed RAS salmon farm in Scotland "***FishFrom***"[38]. This is a proposed £15 million investment at a site at Tayinloan, Argyll with a target production of 3,000t per annum. Larger scale projects are anticipated after this in order to capture economies of scale and market share. The proposed technology provider is ***Aquatec Solutions A/S***.

A second large project in Denmark is ***Danish Salmon*** which has a target production of 2,000 t of 4-5 kg salmon per annum. The farm is located in Hirtshals and is being constructed by ***AKVA group*** Denmark. It is due to commence sales in September 2014 with output already sold to ***Nordic Seafood*** via the local processor, ***OH Fiskeeksport***. This company is one of the five investors in the company (20%), the others being ***CAL Invest*** (30%), ***Medipure Invest*** (25%), ***S Frandsen Gladstone*** (20%) and Bent Urup (5%). It utilises two units of four 16m diameter tanks and eight 6m diameter smolt tanks, each with separate water treatment systems. There is also a hatchery and fry rearing system with separate water treatment using 4m diameter tanks. The total treated water flow rate is 13,000 m^3/hr.

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[35]http://www.alaskasalmonranching.com/sweetspring-salmon-calls-for-investors-to-keep-afloat-part-3-of-4/
[36] www.intrafish.com 24/02/14
[37] https://openparliament.ca/committees/fisheries/41-1/17/john-holder-1/
[38] http://www.fishfrom.com/

The ***Xinjiang E-he Construction and Investment Company***, owner of a RAS salmon farm being built in China, hope production will start around April 2014, with an aim to expand the project in the next five years. The farm is located in the Gobi desert, near to the border with Mongolia, with ***Billund Aquaculture*** involved in design and construction. It is hoped that the farm will be able to expand from producing 1,000 metric tons of salmon to 10,000t within the next five years (Undercurrent News 23 August 2013). Another RAS project in Shandong Province China is the ***Yanai Salmon Farm*** owned by ***Shandong Oriental Ocean Sci-Tech Co***. This has been in production since 2012 and has an annual target of around 1,400 tonnes per year. Its initial marketing strategy was to sell live fish at €25/kg, but sales were reportedly weak and more recent prices have been in the region of €11/kg. This is still sufficient to provide a good profit margin[39].

The ***K'udas*** Project is a collaboration between the ***'Namgis First Nation*** and the ***SOS Marine Conservation Foundation*** to build a pilot-scale land-based RAS on the Cheslakees Indian Reserve, 5 km south of Port McNeill on Vancouver Island. It has supporting funding from a variety of organisations including ***Tides Canada*** (an environmental body), local oil-production interests, ***Sustainable Development Technology Canada (SDTC)***, ***Department for Fisheries and Oceans's (DFO) Aquaculture Innovation and Market Access Programme***, ***Coastal Sustainability Trust***, ***Richie Foundation***, and ***BC Hydro Power Smart***. Opened in March 2013 it should be harvesting its first fish in March 2014. It is a land-based RAS farm with an initial production target of 470 tonnes per annum (with a density up to 90 kg/m^3) and planned expansion to 2 – 3000 tonnes. The project has been designed such that, initially, only one module with an annual production capacity of 260 tonnes to 500 tonnes will be installed. Data collected from pilot operations will then be used to refine the design where necessary and to expand to a full-size. Initial investment, coming primarily from SDTC, Tides Canada and the Coast Sustainability Trust, is around C$7.25 million. The project has been designed with a number of innovative features intended to reduce operating costs and maximize revenues, including heat recovery and heat pump technologies that are estimated to reduce energy costs by a factor of 10. The site is also being designed to eventually accommodate aquaponics, whereby the nutrient-rich effluent water will be used to grow plants in greenhouses.

Marine Harvest Canada is planning to undertake a pilot RAS project in order to document the actual costs and benefits of commercial scale RAS production, and to contrast the collected information with the figures for conventional net pen production. This preparatory work has been completed, and the cost of a 300 tonnes per year pilot on the east coast of Vancouver Island was estimated at $8 million. Partial funding for the project was committed by DFO and SDTC. Although Marine Harvest had intentions to proceed based on these preliminary studies, a reduction in the world market price of salmon resulted in the required $5 million in funding from Marine Harvest's parent company not being approved and the project was put on hold while alternative funding sources were sought or until the market price of salmon improves.

An Abu Dhabi company, ***Asmak***, is planning an Atlantic salmon RAS farm that can compete favourably with imports flown in from Norway or Ireland which entails significant air freight costs ($4-5/kg) in a bid to provide affordable alternatives to popular local fish such as grouper while substituting imports.

4.3 Intermediate strategies

Over the past ten years there has been increasing investment in RAS farms for salmon smolt production in Scotland, Norway and Chile. These systems are reputedly cost competitive with alternative cage-based systems. One scenario is that juvenile salmon could be reared to a larger size in land-based systems before

[39] https://www.seafoodsource.com/en/news/aquaculture/13791-china-firm-cultivating-salmon-for-live-sales

being moved to sea for final growout. This is currently being tested in Norway in a joint industry research project with Nofima (Terjesen et al, 2013). The rationale for this is:

- The highest losses during the marine farming stage is from post-transfer smolts (up to 20%)
- Post transfer smolts can have reduced feed intake and growth rates
- Lice problems are increased with longer growout periods
- Shorter growout at sea would enable farms to improve utilisation of sites and allowable biomass limits

The Norwegian government recently adjusted regulations that previously required all salmon over 250g[40] to be cultured in sea cages to a new limit of up to 1 kg in tanks. Strategies are being tested with the fish smolting at normal size and then being reared in seawater RAS or being maintained in freshwater, seawater or intermediate salinities. Preliminary results indicate that a salinity around 12 ppt and a water flow velocity that exercises the fish would produce the best results providing fish are maintainted to at least 800g. Between 400 and 700g the fish were very sensitive to handling and salinity changes. A lower salinity for rearing would have the following benefits (compared with full salinity):

- Increased feed intake and growth rate
- improved skin health
- Improved removal efficiency of ammonia and carbon dioxide
- Improved overall survival rates

Problems of early maturation do not occur in low salinity RAS units up to 1 kg.

The same project in Norway is also testing the option of initial grow-out from 100 g to 1 kg in a floating closed containment tank (in collaboration with Marine Harvest). This has a volume of 21,000 m^3, with a pumped water flow rate of 450 m^3/min. Similar systems developed by Agrimarine Technologies Inc. are being tested in Canada and China[41]. Initial designs draw water from around 30m depth to help avoid drawing in algal blooms or parasites. Additional water treatment on the inlet might be considered in the future. The outflowing water passes through a sedimentation process to reduce the discharge of solid waste. More substantial screen filters will probably be installed if the system is adopted. There is no treatment for dissolved wastes. Floating tank solutions are promoted by several conservation groups as an acceptable solution to containment (e.g. Pure Salmon Campaign[42]), but also pose numerous challenges and are not considered further in this report as they do not constitute recirculated systems. Based on their trials in China, AgriMarine estimated production costs at C$4.56/ kg making favourable comparison with Marine Harvests estimate of C$4.50/kg for cage-production in British Colombia. However other industry experts remain sceptical of this claim[43]. Like many other such initiatives the project has benefited from considerable public sector (C$7.5m) and e-NGO funding support AgriMarine reported losses of C$2.1m in the six-months to Oct 2010 by which time it had an accumulated deficit of $14.5m. Their demonstration farm in Vancouver suffered considerable damage and loss of stocks during a storm event in 2008 which left other conventional farms in the same area entirely unaffected[44]. In its 2011 report leading salmon producer opined: "*Closed-containment technology does not currently represent a viable alternative, especially related to energy usage but also [fish] escapes remain a risk in closed containment farming.*"[45]

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[40]Limits imposed as part of strategy to limit feed inputs into fresh water systems
[41]http://agrimarine.com/
[42]http://www.puresalmon.org/closed_containment.html
[43]http://www.theglobeandmail.com/news/british-columbia/bc-developer-touts-salmon-rearing-tank-over-fish-farms/article564701/
http://www.alaskasalmonranching.com/agrimarine-profits-and-fish-swim-away-literally/
[44]http://responsibleaquaculture.wordpress.com/2012/04/19/2700-escapes-from-agri-marine/
[45]http://www.seafoodintelligence.com/EditModule.aspx?tabid=1&mid=382&def=News%20Article%20View&ItemId=30750

Figure 10: An Agrimarine floating closed containment system being prepared for installation[46]

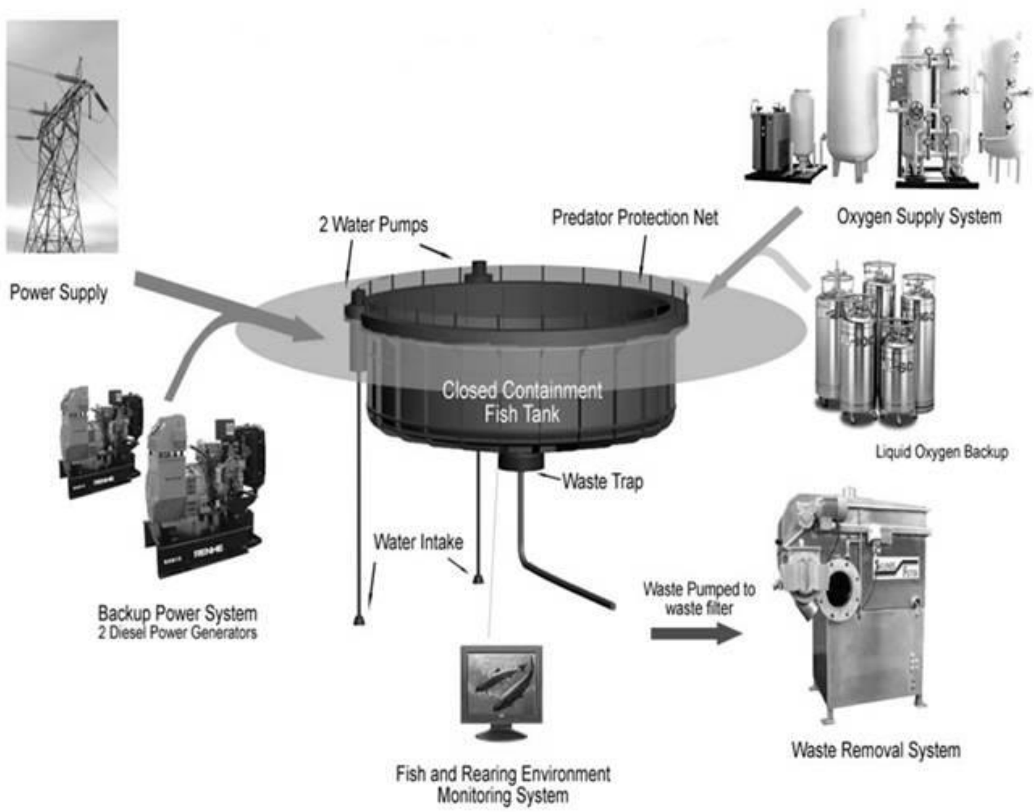


Figure 11: Diagram of floating closed containment system with key ancillary equipment[47]

[46] http://www.davidsuzuki.org/blogs/healthy-oceans-blog/2011/01/another-breakthrough-in-better-salmon-farming/

[47] http://www.parl.gc.ca/HousePublications/Publication.aspx?DocId=5994887&Language=E&Mode=1&Parl=41&Ses=1&File=84

4.4 Technical issues for salmon production in RAS

Promoters of RAS-based salmon production present recirculated systems as having highly controlled environments which can therefore be adjusted to optimise growth and other performance parameters. With the current status of technology however, especially in marine RAS, this cannot be taken for granted. The systems are highly complex involving interactions of water chemistry, microbial flora and fauna and fish physiology, not to mention feed components and waste products.

One solution advocated to remove some of the complexities of marine RAS is the complete grow-out of salmon in freshwater. The Freshwater Institute in Virginia, USA conducted pilot trials in 2011 and 2012 (Summerfelt et al, 2013). They reported growth rates comparable with cage farming, indeed somewhat faster than farms that have to over-winter the fish at low temperatures. This is illustrated in the figure below, which needs to be interpreted with some care. Although the fish in the two trials were from the same basic genetic stock, they were of different parents and early rearing was carried out in different facilities. Feed type and management may also have differed significantly. Most importantly, the stock in the Freshwater Institute trial contained a high proportion of grilse (80% of males, so 40% of total stock compared with 4-6% in the cage trial (Wolters, 2010)), which were harvested early. The comparison is therefore biased by this large cull of slower growing fish earlier in the production cycle. Unless a population is frequently graded there will be a significant spread of sizes (usually with a normal distribution). For a stock with an average weight of 4.5 kg, the spread is likely to be between 2.5 and 6.5 kg. Removing a smaller size grade from consideration can therefore have a substantial impact on measured average size.

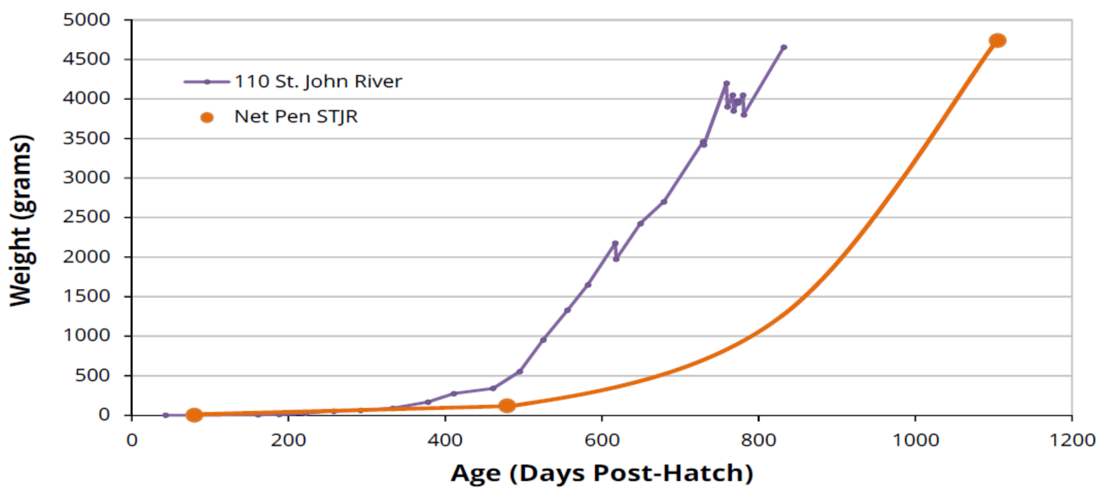


Figure 12: Growth data from Freshwater Institute trials with Atlantic salmon compared with cage site in Maine (Source: Summerfelt et al, 2013)

Relatively little data is available from commercial salmon farms, but unpublished analysis of such data from a wide variety of locations (Talbot pers. comm.) suggests that higher temperatures do not necessarily lead to shorter times to harvest weight (in part due to adaptation mechanisms).

The problem of high grilse rates was faced in the cage-based salmon industry (although rarely as severe), particularly in lower-salinity sites. This was addressed through selective breeding for late maturing males and/or photoperiod manipulations. For freshwater RAS farms the use of all female (and perhaps triploid) stock could be considered.

The feed conversion rate during the Freshwater Institute trial was 1.01which compares favourably with cage-reared salmon. Mortality rates were also very low (below 5%). Stocking densities reached 100 kg/m^3. As with other RAS for growout, off-flavour taints were reported as a problem, requiring depuration of 10-14 days. Photographs included in the report suggest that the fish have less silver colouration than would be normal for sea reared salmon and there may be other differences that would affect market value. The report does include the results from a blind taste test which showed the panel preferred the RAS reared salmon to cage-reared salmon. This appears to have been due to a higher fat content in the fillet for the RAS reared fish so may be subjective and dependent on markets.

Good et al (2012) considered a range of operating conditions for salmonids in RAS. They found growth rates somewhat higher for salmon reared under a regime of continuous light followed by a simulated winter of 12 hours light and 12 hours dark for six weeks before a return to continuous light. Investigations on the effects of elevated CO_2 levels showed no significant difference in growth or survival rates when concentrations were 10 or 20 mg/l. Small differences were found in feed conversion rates and some physiology indicators suggesting some sub-lethal effects at higher CO_2 concentrations.

The same study found increased growth, better feed conversion, less size variation at harvest, reduced aggressive behaviour, improved disease resistance and improved flesh texture when exercise levels were higher (current speeds of 2 body lengths per second compared with 0.5 body lengths per second). Greater exercise is also related to higher oxygen consumption, making low oxygen concentrations more critical. Experimental work comparing growth rates at 70 and 100% saturation concentrations showed growth rates reduced at the lower oxygen levels.

Further work with juvenile rainbow trout comparing different rates of water exchange and hence different dilution rates investigated the impact of higher concentrations of metabolites and other compounds. Fish in a near zero exchange system were observed to have much higher incidence of "side swimming" and increased incidence of spinal deformities. These were associated with elevated concentrations of nitrate nitrogen, potassium and copper (Davidson et al, 2011). This underlines the need for higher levels of water monitoring and treatment in very high rate RAS. Additional experimental work with systems maintained at 29 and 89mg/l nitrate nitrogen found higher nitrate levels to significantly and adversely affect food conversion efficiency, survival rates and percentage of side swimmers (Good et al. 2012)

4.5 Economic appraisals and prospects

This analysis focussed on the Danish Langsand Lax venture initiated in 2010, the first land-based RAS to begin to produce table-salmon commercially. Although a production of 700t if forecast in the first year of operation and there are plans to scale the operation up to 4000t/yr, this analysis is based on the current production capacity of 1,000t growing fish to a mean harvest weight of 4.5kg. Justification for the development at the Langsand site included proximity to existing engineering and farming skills, pre-existing environmental licenses associated with a previous aquaculture operation, infrastructure and other pre-conditions good for a rapid and on-cost build and availability of a generous government capital investment subsidy. Considerable thought was also put into use of cost-effective materials (e.g. use of sectional concrete surface mounted tanks) and low-cost procurement. Elements of the technology were also pre-tested by a sister company (Billund) in Chile.

A former 250t flow-through trout on the site was demolished and a co-located RAS eel farm converted to a hatchery permitting concurrent preparation of smolts for immediate stocking whilst the grow-out 'Oceanus' RAS was under construction by partner Billund Aquaculture (established in 1986, Billund has built over 100 RAS for 25 kinds of warm, cold, salt and fresh water fish in 25 countries). The hatchery, capable of supporting the planned production capacity of 4000t, yielded its first smolts in 2011 and the first salmon were harvested in January 2014.The farm uses low salinity salt-water (15-20ppt) extracted from a nearby fjord and also incorporates denitrication plant to increase recirculation rates. This modification was in part a response to concerns regarding waste-discharges into the fjiord by national environmental and fishing lobbies.

Capital and operation costs were further reduced by installing relatively few grow-out tanks; 8x 10m diameter tanks (used for smolt on-growing/ grading and depuration of the harvested fish) and 4x 17m grow-out tanks. The post smolt-grow out period is around 10 months; with 5 months in each of the 10 and 17m diameter tanks. The companies CEO Thue Holm estimated that costs of the investment could have been double, if additional grading capacity had been installed for the grow-out phase[48]. The downsides of this compromise include higher risk associated with failure of individual tanks and a wider range in the size of the harvested product ranging from 3 to 6 kg (mean 4.5kg). Although markets exist for smaller and larger salmon – clearly this does limit the ability for strategic market planning compared to cage-systems.

Figure 13: Large tanks at Langsand Laks RAS salmon farm in Denmark (Source Atlantic Saphire)

Production costs itemised in Table 6 are estimated at €1.65 per kg for basic operational costs rising to €3.10/kg (farm-gate dressed head-on bled on ice) including financing, depreciation and all other costs. This is slightly below the current farm-gate price for Norwegian salmon (around NOK 30). Holm accepts that his costs are between 20 - 30% higher than those of 'the most efficient' Norwegian salmon farm. Profitability is therefore based on ability to secure a premium and scalability. Holme estimates that his product can secure a 30-40% premium in the 'high-end' food service sector based on sustainability attributes and a leaner product from exercised-fish cultured in flowing water. However scaling up to 4,000t clearly also risks saturation of this market. Initial target markets for air-freighted fresh/chilled include the UK, the USA and the Far-East. However, the company and its associates are already involved in plans to develop similar scalable installations in the USA (through a consortium called Atlantic Sapphire; planning for 16,000t/yr) and China (Billund Aquaculture; planning for 10,000t/yr) in which Langsand's role as an incubation unit may alone justify its investment.

Production costs of €3.10/kg for the Langsand 1,000t/yr compare with only €1.40/kg costs (against wholesale prices around €2-2.50) for the 600t Fishion tilapia farm described in section 2.3 suggest that considerably larger-scale salmon RAS will be necessary for profitable operation compared to requirements for freshwater species such as tilapia and catfish.

The potential for scale economies in salmon RAS must also be evaluated in the context of developments in the cage-sector. As part of a long-term consolidation trend, farms in Scotland, Norway and Chile and have been growing larger in size with significant associated productivity gains, accompanied by the closure of smaller farms in more enclosed and environmentally sensitive water bodies. Marginal costs for this kind of up-scaling are likely to be considerably lower than for comparable increases in RAS scale. As there are no reliable reports of any RAS system having produced more than 1,000 t/yr to date, any claims around the scaleability of RAS systems remain largely a matter of supposition.

[48]http://www.aquacircle.org/modules/default.aspx?pageid=8&newsid=797

A report on closed containment, commissioned by the Canadian Government[49] concluded that Pacific salmon can be raised profitably at scales of 1/5th to 1/10th of the '1,000t' minimum for Atlantic Salmon as they are less commoditised and 'provide better opportunities for niche marketing'. However, the rise of Atlantic salmon is also a consequence of fundamental product attributes suggesting even greater potential for saturation of the niche-markets for these substitutes. The report finally concludes: 'closed containment systems have proceeded far enough along the innovation chain that government funding of commercial-scale demonstration projects is now necessary before full commercial deployment can be expected by the private sector.'

Table 6: Estimated operational costs for production of 4.5kg salmon (LWE) from a 1,000t/year capacity salt-water RAS – excluding labour and financing costs (source Langsand Lax)

Item	**Price €**	**Units & unit costs**
Smolts (including egg cost)	0.47	125g individual smolt weight
Feed	5.25	€1.15/kg smolt feed: (EFCR 1,05)
Oxygen liquid	0.31	€0.18/kg oxygen
Energy	0.71	€0.10/kg (kWh)
Heating and cooling	0.11	€0.10/kg (kWh - heat pump)
Carbon source	0.26	€0.4/ litre (alcohol)
Iron chloride	0.06	€0.54/ litre
Polymers	0.2	€2.68/ litre
Sludge	0.09	€13.5/ ton removed
Base buffers	0.08	€0.17/kg (lime)
Total	**7.38**	**Per fish @ 4.5 kg mean harvest weight**
Total	**1.65**	**Per kg of fish LWE**

[49] Parliament of Canada 2012 Closed containment salmon aquaculture report
http://www.parl.gc.ca/HousePublications/Publication.aspx?DocId=5994887&Language=E&Mode=1&Parl=41&Ses=1&File=84

5 Potential for commercial RAS in HIE area

5.1 Candidate species and technologies

As recirculation systems are expensive to purchase and operate it is usually only economically viable to farm high value species or life-stages in these systems. Other species-specific determinants of profitability include length of culture period from stocking to harvest and upper biomass stocking density limits (Table 7).

Table 7: Classification of candidate food-fish species for European RAS based on key culture characteristics

Life stage	Optimum Temp range (°C)	Culture period (months)	Upper Biomass (kg/m^3)	Candidate species	
				Fresh water	**Salt water**
1. Juveniles	10-18	4 - 8	60 - 70	Salmon parr/ smolts	Turbot, halibut, cod, Dover sole, seabass, sea bream
2. Table-fish (& caviar)	Temperate 12-20	12 - 24	50 - 70	Sturgeon[1], Arctic char, perch	Turbot, Dover sole, Senegalese sole, Salmon
3. Table-fish	Intermediate 16-24	8 - 12		European eel, rainbow trout	Seabass, seabream, yellowtail kingfish/amberjack
4. Table-fish	Warm-water 24-28	6-8	60 - >300	Barramundi, African catfish[2], tilapia[2]	Red drum (Cobia, grouper)

[1]Given the high value of caviar, achieving high stocking density is a lower management priority for sturgeon
[2]Although fast growing and tolerant of high stocking density, these fresh species command low prices

Table 8 Commercially important species for RAS culture by region

Europe	Other
Salmon (smolts)	Murray Cod
Eels	Jade Perch
Seabass/ bream	Silver perch
Barramundi	Cobia
Turbot	Shrimp
Sole (mainly Senegalese)	Abalone
African catfish	Seahorses
Tilapia	Grouper
Sturgeon	Red Drum
Ornamentals	

The most viable finfish species are likely to be fast-growing and higher unit-value warm water species such as European sea bass, *Dicentrarchus labrax*; gilthead sea bream, *Sparus aurata*; Senegal sole, *Solea senegalensis*, and yellowtail, *Seriola lalandi.* Several other seafood species such as abalone are feasible but ideally these species should be developed in conjunction with a more established RAS projects using a proven RAS technology approach and farming a species whose culture technology is well established.

Sea bass and gilthead bream are key farmed Mediterranean species and as such HIE production would sometimes need to compete with low priced product being imported to the UK by Greece and Turkey. However, the large scale production (3-5 thousand tonnes pa) of these species in HIE encompassing hatchery and value added processing might be worth consideration. RAS technology for producing sea bass has been established in the UK in a single project, and provided stable management continues then the farm is on course to become profitable during 2014.

The Yellowtail Kingfish, *Seriola lalandi* (and the related amberjack, *Seriola dumerii*) are subtropical species distributed worldwide preferring warm water between 18–24°C. Culture techniques are established and 1.5 – 2.5kg fish can be achieved in 12 months. These are high value species marketed as whole, cutlet, steak or filleted form but also regarded highly as sashimi and used in teriyaki and zoni (soup). They are already farmed commercially in Europe using RAS technology and can be considered as an alternative to tuna.

The commercial production of sole currently takes place mainly in Spain and Portugal with *Solea senegalensis* being the preferred species. Production levels of this species increased from 110 tons in 2008 to 500 tons per year in 2010 (Howell et al., 2011). However disease control, particularly Pasteurellosis, and feed related problems such as poor growth rates and feed conversion ratios are the main factors affecting production performance. Most companies have reported problems of poor growth, disease in the nursery and ongrowing stages, and difficulties in spawning of F1 and F2 stocks. Feed formulation and management of production systems were also reported as problem areas. The majority of producers are now based on the Atlantic coast of Spain and Portugal with one producer in the Canary Islands and one farm producing Dover sole in Holland. Most production is from on-shore tank systems, either shallow raceways or conventional tanks, often in conjunction with recirculation systems. Requiring an optimum temperature of 19 – 20°C (García & García, 2006) S. *senegalensis* would be an ideal species for HIE once the technology becomes better established. Alternatively, it could be produced as a follow-on species alongside a better established species such as sea bass where the technology for production in RAS is far more advanced.

Despite the reported difficulties with sole some research has indicated high growth rates of *S. senegalensis* in shallow raceway systems at relatively high densities (up to 60 kg/m^2). The lack of density effect on growth was thought to be due to improved water quality in the micro-environment surrounding the fish, food distribution patterns that prevent dominance of the food supply by larger fish and reduced interaction between individuals forced to orientate and maintain position against a current (Howell et al., 2011). While higher densities may impact disease susceptibility of this species, RAS technology has been clearly shown to result in a very significant decline in disease outbreaks of species like sea bass farmed in UK RAS. This species is highly susceptible to viral and bacterial diseases under cage production and if proven RAS technology was applied to *S. senegalensis* culture, then progress is more likely. Several researchers working with *S. senegalensis* note that stable water temperatures and water quality is a critical requirement of this species (Howell et al., 2011). This is hardly a surprising conclusion and poor quality RAS design has perhaps been an issue with establishing the precise culture requirements of sole species under different research initiatives.

Good RAS technology has already been developed for other sole species such as the half-smooth tongue sole (*Cynoglossus semilaevis*) (Huang et al., 2013). The RAS system was operated at approximately 95% reuse. Compared to two conventional flow-through systems, the RAS improved survival, growth, and feed conversion ratio, and also maintained a five-fold greater stocking density. During the 8-month commercial production cycle, no catastrophic losses occurred, and 41.5 metric tons of fish were harvested with 97% survival.

5.2 Competitive environment

Apart from feed and labour the key production cost of UK RAS farms will be energy costs related to purification and circulation of water and some temperature control according to RAS design quality and target species. Consequently, while RAS design is critical to minimising energy costs, the selected target species for a RAS farm in the HIE is also very important to maximise opportunities of a financial return. Where a farmed RAS species has significant competition from a national or imported source of the same product, with lower production costs, then the economic risk escalates. Claims of greater sustainability do not always translate into a premium price for RAS production in the market place. Neither should RAS technology be viewed as resolving all potential parasite and disease issues inflicting farmed fish species.

Ideal seafood species for RAS production in HIE should already have high value markets in the UK preferably with an option for expansion. Ideally, they may be warm water species so as to shorten the production cycle (<12 months) which will also reduce the initial capital investment required and lower energy costs associated with cooling. Target species should preferably be secure from competition by supplies from capture fisheries or high volume cage production. Competing against high volume imports of the same species is more challenging but then there could be an economic advantage for larger scale production of such species in excess of 3000 tonnes per annum - possibly even targeting more than one species with similar production demands. Such large scale RAS production benefits from economies of scale and could support the business argument for developing a purpose built hatchery so that fry production is controlled from within the UK. For instance, a former failed UK RAS project producing Asian Sea Bass was dependent on fry imported from Israel or Australia. This presented both economic and bio-security issues. The situation was further complicated by the fact that the species was unknown in UK markets and had to compete directly with European sea bass supplies. In Scotland, large scale RAS farm production of species like bass and bream could also support value added processing enabling the farm to diversify product range and marketing strategy while simultaneously enhancing its sustainability image as opposed to the imported products.

To some extent, provided suitable water supplies are available, RAS production enables location closer to the main markets. In Scotland, development of industrialised RAS production would be most suited to the larger towns of the east coast such as Aberdeen, Inverness, Dundee and Edinburgh. If RAS is to truly represent sustainability criteria then the opportunity to reduce transport miles associated with processing or delivery of product to market should be promoted. Equally, such industrialised units should not impact sensitive environmental areas or areas of outstanding national beauty otherwise they fail to fulfil the objectives of sustainable aquaculture technology.

5.3 Economic appraisal

5.3.1 Economics of RAS Production of Atlantic Salmon

Two economic feasibility studies (Wright & Arianpoo, 2010 & Boulet et al., 2010) both demonstrate that at least under certain circumstances, closed containment could show positive returns. The Boulet et al (2010) feasibility study demonstrated that a 2,500 tonnes per annum RAS farm would require an initial capital investment of $22.6 million and annual operating costs of $7.2 million in order to generate an annual net profit of $381,467. This corresponds to a rate of return of 3.4%. The study also showed that a similar capacity cage operation would require an initial capital investment of only $5 million and would generate an annual net profit of $2.6 million (for an expected rate of return of 40.3%). In contrast, Wright & Arianpoo (2010) suggest that a 1000 tonne pa RAS farm could be significantly more profitable than the above study. This is unexpected since economies of scale seem not to work in favour of the larger farm. The smaller farm analysis resulted in required capital costs of approximately $12 million for a net annual income of at least $5.1 million (or up to $8.2 million if a 25% sustainable premium is factored in). Furthermore, net annual income was reported to climb to between $9 and $13.1 million if the nutrient waste stream is utilized for aquaponics and compost (although it is not clear how the cost of production and marketing are taken into account for these additional products).

Another report from the Norwegian research institute NOFIMA (Iversen et al, 2013) compared unit production costs across the range of technologies. It found land-based recirculating system costs were likely to be around 27.6% higher than inshore cages (used as the baseline). However, land-based RAS would be only 13% higher than offshore farming and 9.3% lower than offshore contained systems (floating tanks). A costing for land-based RAS in a lower-cost country was also developed. It is not specified what country this might be and it seems unlikely that many countries would be able to achieve lower costs across the full range of input factors. However, a possible example might be China, if large-scale development was to take place there. These assumptions lead to a cost of production that is actually 2% lower than the baseline production cost in cages in Norway.

Table 9 Comparative cost of production of Atlantic salmon per kg in different systems (NOK/kg)

	Baseline (inshore cage)	**Landbased recirculating**	**Offshore cage farm**	**Contained offshore**	**Contained inshore**	**Low-cost country RAS**
Smolts	2.19	1.94	2.19	2.06	2.06	1.00
Feed	11.19	9.77	11.19	10.66	10.21	9.77
Insurance	0.13	0.06	0.13	0.13	0.13	0.05
Salaries	1.61	1.97	3.22	2.82	2.42	0.98
Depreciation	1.09	2.78	1.67	5.71	3.13	1.88
Lice treatments	0.66		0.66			
Fish health & medications	0.50	0.25	0.50	0.5	0.50	0.20
Administration	0.20	0.40	0.20	0.20	0.20	0.20
Electricity		1.68		0.84	0.84	1.68
Oxygen		0.77				0.77
Sludge		0.14		0.07	0.07	0.14
pH control		0.07				0.07
Other	2.01	3.02	2.01	2.51	2.51	1.51
Capital	2.27	5.71	5.71	6.00	4.06	4.36
Slaughter	2.53	2.53	2.78	2.78	2.53	1.27
TOTAL	**24.36**	**31.09**	**27.51**	**34.28**	**28.65**	**23.87**

Source: Iversen et al, 2013 (Note NOK 10 is approximately £1)

The variance in these predictions was examined, indicating a high degree of confidence in the difference in cost between inshore cages and land-based RAS, although the difference between Offshore cages and inshore contained systems was much closer.

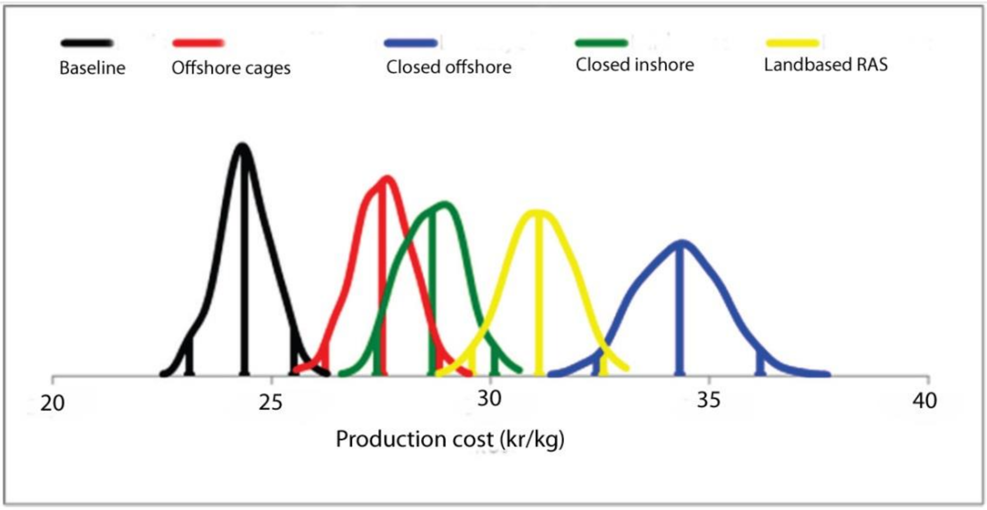


Figure 14: Probability distribution of production costs for the various system options

(Source: Iversen et al, 2013)

As shown in the table below. This comparison does not compare systems of comparable scale (i.e. the contained systems are 3,300 tonnes per year and the cage systems are 10,000 tonnes per year) however, this is probably a reasonable assumption in terms of achievable scales based on currently available technologies. Some assumptions may also need modification for the Scottish context (for instance stock insurance premiums are currently likely to be higher in RAS than in conventional cage farms).

Table 10 Assumptions used in the above analysis

	Baseline (inshore cage)	Landbased recirculating	Offshore cage farm	Contained offshore	Contained inshore
Production (t/yr)	10,000	3,300	10,000	3,300	3,300
Productivity (kg/m^3/yr)	30	180	30	70	80
Investment (NOK per m^3)	219	10,000	500	4000	2500
Current assets (NOK/kg)	23	20.6	23	23	23
Depreciation (years)	6.7	20	10	10	10
Mortality (%)	20	10	20	15	15
Smolt price (NOK)	8.75	6	8.75	8.75	8.75
Economic FCR	1.26	1.1	1.26	1.2	1.15
Feed price (NOK/kg)	8.88	8.88	8.88	8.88	8.88
Stock insurance	0.5%	0.25%	0.5%	0.5%	0.5%
Equipment insurance	0.15%	0.10%	0.15%	0.15%	0.15%
Oxygen (kg/kg feed)		0.35			
Price oxygen (NOK/kg)		2			
Sludge (kg/kg feed)		0.25			
Price sludge (NOK/kg)		0.50			
Alkalinity (kg/kg feed)		0.25			
Price of alkalinity (NOK/kg)		0.25			
Employees		10			
Employee cost (NOK/person)		650			

Source: Iversen et al, 2013

In a further comparative financial assessment of RAS and caged farmed Atlantic salmon performed by the US Freshwater Institute and SINTEF, Norway, (Rosten et al., 2013), a constant production capacity of 3,300 tonnes was assumed for both cage farm and RAS. This defined an investment cost of US$ 32 million (~£20 million) for the RAS farm and US$ 12.3 million (~£7.7 million) for the cage farm. Operating costs however were estimated at US$ 3.98/kg for RAS and US$ 4.24/kg for the cage farm, in part due to substantially lower electricity prices in the USA (US$0.05/kWh compared with $0.17/kWh in Norway).

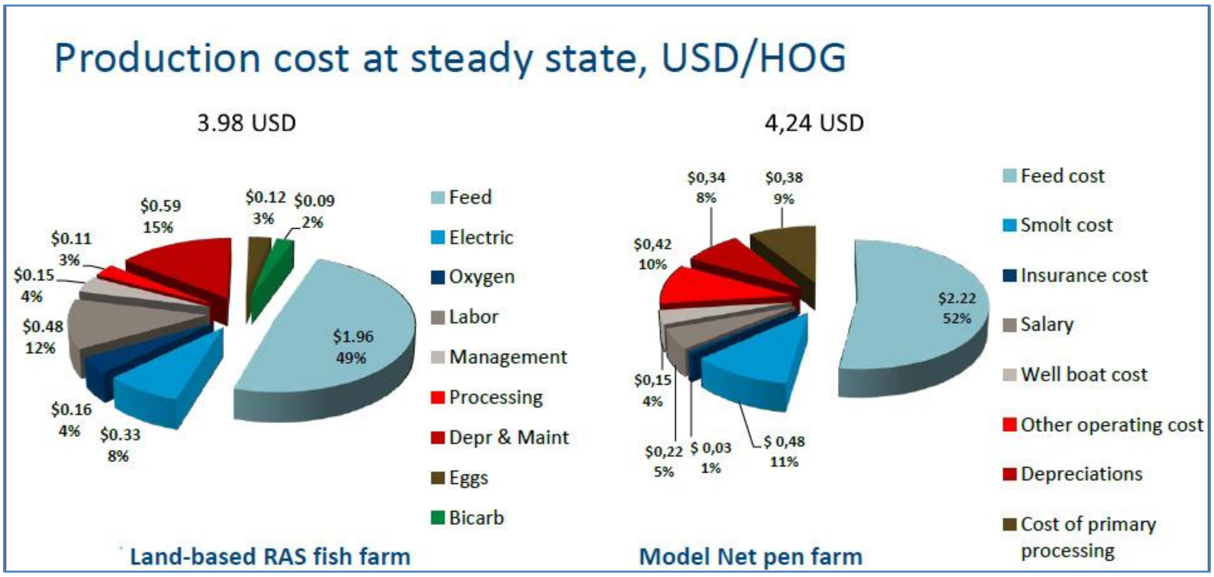


Figure 15: Comparative operating costs for similar scale land-based RAS and cage farm
(Rosten et al, 2013)

Overall the study concluded that:

1. Production cost in RAS was not higher than in cage farms
2. The RAS farm would provide a lower rate of return on investment if a premium price was not secured.
3. RAS production of Atlantic salmon has a higher CO_2 footprint unless a significant proportion of energy comes from a sustainable source.
4. Feed efficiency is the dominating parameter of the carbon footprint of the salmon production
5. Construction of the production facility and equipment is not an important contributor to the total carbon footprint of salmon production, but the ability to produce closer, or choose transport to the market is potentially important.

The key issue regarding all these studies is that they incorporate a large number of assumptions – and there lies the weakness. Interestingly, Danish RAS salmon farming operation at Langsand Laks has just released its first salmon production to the market. The company intends to market 15 tonnes per week eventually increasing production from 1,000 metric tons to 4,000t, selling to the US, Scandinavia and the UK. In 2014, target production is 700t but the facility should produce 1,000t. Langsand focuses its selling around creating a brand of its sustainable credentials; no sea lice, no impact on the seas, and a leaner, more controlled product. The company applies a 30 – 40% price premium on its salmon, as it sells to high-end foodservice customers. The production costs of the Oceanus system are 20 – 30% higher than those of the most efficient Norwegian cage salmon farmer (Ramsden, 2014). Operator Thue Holm argues that it makes more sense to invest NOK40m in a land based RAS farm than NOK50m for a cage license in Norway. Furthermore, with an FCR <1 Holm suggests that the savings in feed will balance out the energy costs of production (Fischer, 2014).

The production costs noted for Danish Salmon is based on actual commercial scale production within a modern design RAS farm does lead to some questioning of the assumptions and conclusions of the Sintef / Freshwater Institute study (**Rosten et al., 2013**) which appear rather optimistic. Further problems might arise in terms of the volume of such product that can be sold at a premium price – should sufficient market demand for a premium product even exist. Furthermore, given the high stocking densities (up to 100kg/m^3) required to reduce production costs, it may be argued by consumers that RAS production does not take animal welfare into account irrespective of the farms ability to optimize water quality conditions within the production tanks.

Investment in RAS production still tends to favour species that can naturally secure a higher market price in their own right without hypothetical premiums. In the UK, it is debateable if this includes commodity species already farmed at commercial levels using low production cost systems. Even species perceived to be a higher value product like sea bass can struggle in the face of imported product. The only commercial scale UK sea bass RAS farm operating at 95% recirculation at stocking densities of up to 70kg/m^3 has taken longer than expected to enter into profitability. The delay in achieving this goal has largely been due to the early management of the project during development rather than any major design or technology issues related to the water treatment plant. Furthermore, weak market prices of European sea bass during the recession combined with the off-loading of cheap product from Mediterranean suppliers have all served to impact progress of the farm.

5.3.2 Economics of RAS production of other species

Data on the economics of RAS production is generally limited and will clearly be partially dependent on scale and location and heavily dependent on species and system design. The following table can only be taken as a sample of theoretical and actual systems

Table 10: Example RAS investment and production cost data (salmon data for comparison)

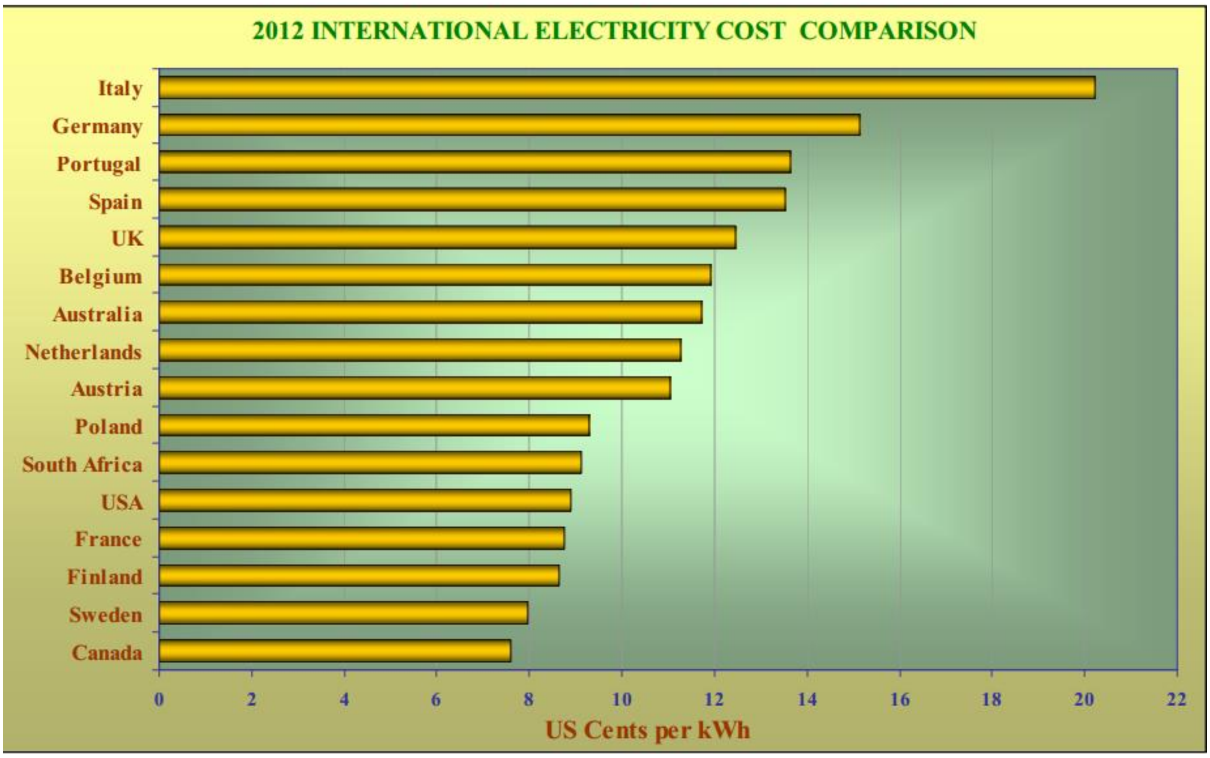
System/Reference	Annual production (t) (and kg/m^3/yr)	Capital cost*	Capital cost per tonne capacity	Annual operating cost*	Operating cost * per kg production**
Tilapia (STAQ Feasibility study)	500 (334)	£1.0 million	£2,000	£1.366 million	£2.79
Barramundi (Inter Aqua Advance feasibility study†)	600	£2.1 million	£3,500	£1.2 million	£2.00
Turbot (Seafish feasibility study†)	100	£1.1 million	£11,000	£770,000	£7.70
Aquafarms, Canada, Steelhead trout	100	£0.77 million	£7,770/t	£333,333	£3.33
Yellowtail, Pilot farm, Netherlands	100 (250)	£0.56 million	£5,580/t	£1 million	£10.00
Salmon, Namgis Farm, Canada	470 (180)	£5.375 million	£11,4365/t	£1.156 million	£2.50
Salmon (based on data from Freshwater Institute and Nofima study)	3300 (180)	£19 million	£1,000 per m3 £5,757/t	£10.26 million	£3.06 (£2.45 projected by Freshwater Institute)

*Where appropriate, the following exchange rates have been used £1 = $1.6, NOK 10, CAD 1.8, Euro 1.2

**Approximate – generally head-on, gutted in boxes. † Inflated to current prices

It is interesting to note that the actual cost of the Namgis farm in Canada was $9.6 million including cost of building delays, compared with an original budget of below $7 million (around 20% increase). This confirms the findings of Jeffery et al (2011) that a 15-40% overspend on budget is common. The same study found it difficult to obtain cost of production data, but quoted one tilapia producer (which had gone out of business) as achieving £1.50/kg and a turbot facility (also closed) at £7.70/kg. Most farms in the survey had failed to reach their projected selling price. One farm had projected £16/kg, but the best price achieved was £3.20/kg and the average only £2.40. Sites producing tilapia or catfish indicated £3/kg would provide a viable business, but were struggling to achieve £2.20 - £2.80. Although feed is generally the largest component of operating costs, energy was also found to be a major contributor (15-20%). The cost of energy could therefore be a factor in influencing the location of RAS farm developments. At present the lowest prices are probably in some Gulf States. The UK does not have the highest energy prices in Europe, but is above average.

Figure 16: International energy cost comparison (2012)



Source http://www.kraftaffarer.se/meralasning/2012E&GSurvey.pdf

The investment cost of RAS becomes a more critical element when loan financing is required. In addition to adding interest payments to operating costs, any major delays in achieving full production creates cashflow problems that may require further financing, making profitability even more challenging.

So far there has been relatively little opportunity to consider potential economies of scale in recirculated systems. This is gradually changing with investment in the first 1000t+ farms. Key design targets to maximise economies of scale might include (adapted from Summerfelt, 2013):

- Fewer but larger tanks
- Smaller footprint buildings
- Octagonal tanks with shared walls
- Centralisation of treatment to minimise duplication
- Multiple cohorts and weekly harvests

Economies of scale can be seen to operate in many elements of an aquaculture operation. With respect to capital costs, construction cost per cubic meter of tank volume generally reduces with increasing volume. This is because the ratio of tank wall area to volume decreases with increasing diameter and depth as shown in the figure below. There are significant limits to this effect however, as tank construction also need to be stronger to support the weight of the water contained.

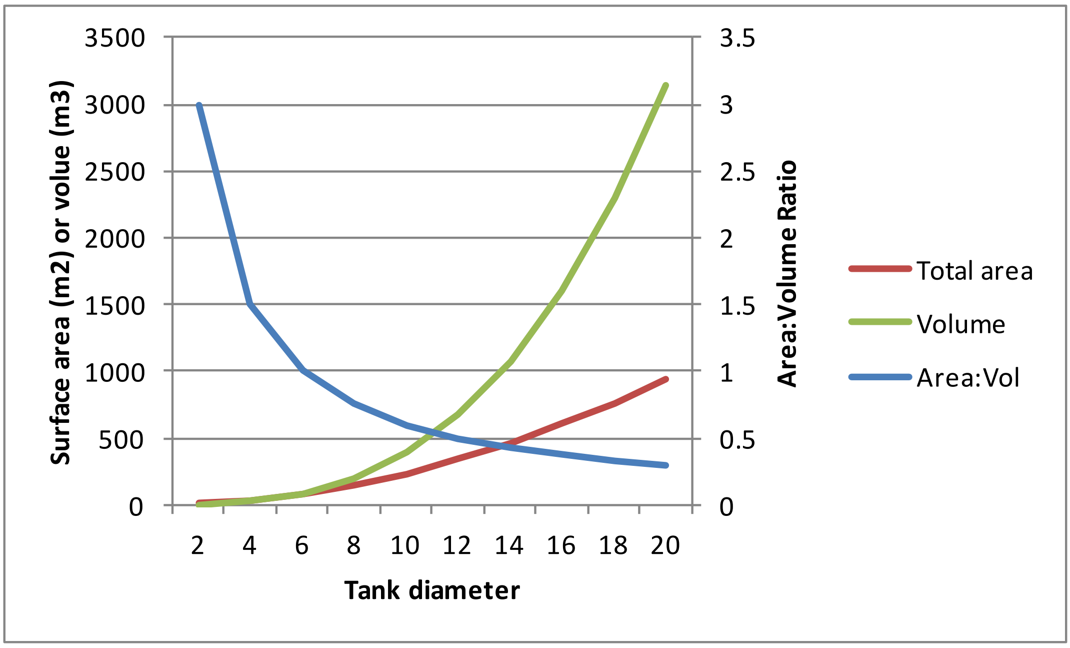


Figure 17: Relationship between tank surface area and volume (where depth = radius)

Similar relationships can be seen with other components such as pumps, where capital cost per unit of power (capacity) reduces with increasing size.

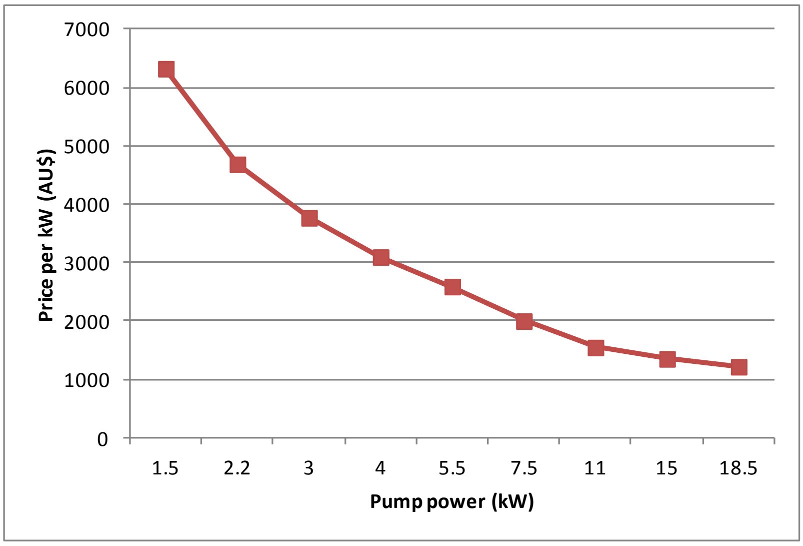


Figure 18: Relationship between pump power and price per kW[50]

[50] Developed from http://www.cnppump.com.au/downloads/Price-List/2011-CNP-Pump-Pricelist-AUS.pdf

Another factor could be the number of RAS farms that are developed. The greater the number individual suppliers build, the better they will be able to spread design and development costs and invest in manufacturing technology for lower cost specialist components.

Probably more important than economies of scale for capital costs are economies of scale on operating costs. The largest single cost is feed. Feed efficiency is unlikely to change with scale (indeed may deteriorate), but there will be discounts that can be obtained through bulk purchasing and overall volume. Transport costs will also reduce to a point if delivery sizes are as large as can be accommodated by the supplier. Electricity costs can also be reduced through bulk purchase. Better documented is the savings that are possible in labour costs. With mechanisation, the number of staff required to manage a farm does not increase in direct proportion to production volume. This is well illustrated by the Scottish aquaculture statistics[51]. In 2012 the average trout farm produced 166 tonnes and productivity per person employed was 53 tonnes. In the salmon industry there were 100 active sites with a mean production of 1,622 tonnes and a productivity of 153.2 tonnes per person. This has risen from 92.3 tonnes per person in 2000 when the average site was only 372 tonnes of production. Scotland is still some way behind Norway however, where productivity was 329 tonnes per person in 2012 on a lower average production per site (1,318 tonnes)[52]. Greater opportunities for the economic utilisation of waste from RAS farms should also develop with increasing point source production and overall volume.

The importance of scale economies in relation to other means of reducing production costs (e.g. through technological advances) is less certain. In an economic study of the development of the Norwegian salmon industry, Asche et al (2013) found no evidence of scale economies, whilst an earlier study (Vassdal & Holst, 2011) considered the main impact of horizontal integration was better sharing of expertise and consequent improvements in management.

An examination of the limited data available (actual and planned) projects indicates some evidence for economies of scale in respect of capital cost although with very large variability (Figure below). At this stage there is little indication of economies of scale with respect to operating costs. It is likely that scale relationships will be better defined by logarithmic or power functions, but at this stage other factors such as location and system design appear to be more important.

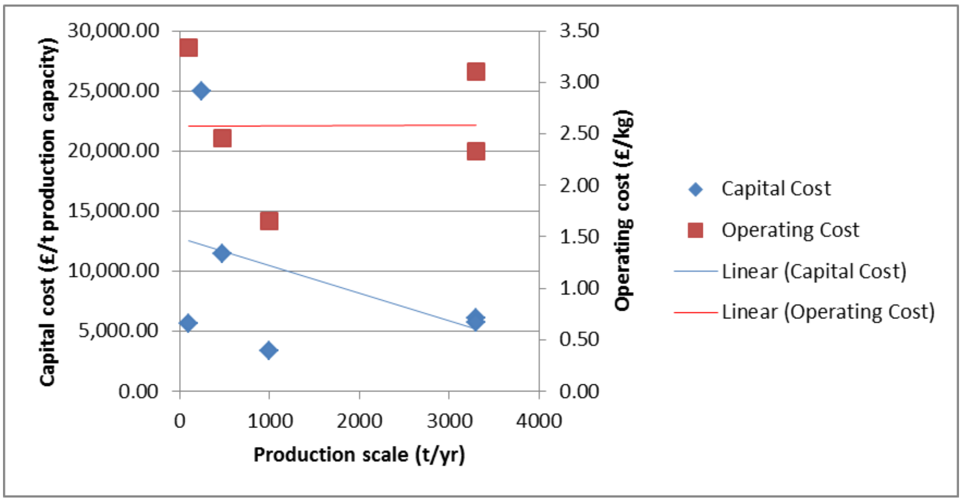


Figure 19: Plot of Salmonid RAS capital and operating cost data against annual production volume

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[51] Data from Annual Fish Farm Production Surveys, e.g. http://www.scotland.gov.uk/Publications/2013/09/9210

[52] Calculated from data at http://www.fiskeridir.no/english/statistics/norwegian-aquaculture/aquaculture-statistics/atlantic-salmon-and-rainbow-trout

6 Implications for HIE area if RAS develop elsewhere

6.1 Potential scenarios

Immediately, RAS production of salmon would unlikely make any significant indent to the volume of caged salmon production in Scotland. However, it's worth considering that 2-3 UK RAS farms collectively producing 5-6 thousand tonnes of sea bass could substitute around 60-70% of imported supplies from Greece and Turkey.

In order to be competitive in the international marketplace, RAS producers could be inclined to locate their operations where input costs were the lowest (such as energy, transportation, water and land costs). If inland locations were economically more attractive, and companies were to relocate, there could be a negative impact on employment in remote coastal regions that currently rely on cage farming for employment.

If RAS salmon production proves to be economically viable then a) pressure will increase on cage sector to further improve sustainability of its production methods b) where feasible RAS production of salmon will move nearer to the main markets whether these are in the UK or abroad. This approach is already being promoted by Norwegian and Danish RAS technology suppliers with RAS production of salmon planned in Abu Dhabi and China – both markets for salmon farmed in Europe. Naturally, RAS production of salmon in these countries, as opposed to Scotland, would benefit from lower energy (critical for pumping and water cooling) and labour costs.

If RAS salmon production expands then UK caged salmon farming may contract in the long term just as it would in other regions of Europe where the product is exported to overseas markets. To protect businesses in national countries, HIE might experience a more severe reduction of salmon production where cage production is owned and operated by non-UK companies. Meanwhile, seafood production in HIE would continue possibly targeting higher value markets and reflecting a greater focus on species diversification to supply national and EU demand.

However, this scenario would still take decades and if RAS technology is to make any real significant inroads into UK cage salmon production then energy costs will need to stabilise while the RAS technology becomes significantly more energy efficient and user friendly for lower value commodity species. Perhaps the caged salmon sectors greatest protection from RAS production is its relatively low market price and the current high capital investment cost of initiating RAS production.

6.2 Market factors

The drivers for salmon production in RAS are far clearer for markets that are some distance from the current major centres of production. Iversen et al (2013) suggests that RAS based production is between NOK 5 and 10 (£0.50 to £1.00) per kg. This translates to between £0.83 and £1.66 per kg of fillet. However as air freight costs are between £1 and £2 per kg for fresh fillets (depending on routes and quantity), the cost advantage of cage-aquaculture is eliminated and local RAS production would have a significant advantage for freshness. This helps to explain the interest and investment that has been noted in China and UAE.

An important question is then whether there is any differentiation between locally (RAS) produced product and imported product from Scotland (or other users of cage technology such as Norway and Chile. It is probably too early to determine this with any certainty. At the present time, more trust is placed in imported foods than in locally produced foods in China due to a long history of contamination and adulteration scandals. Chinese consumers are also increasingly responding to brands and are likely to value a produced in Scotland label. On the other hand, Chinese consumers are used to very fresh product (fish are frequently purchased live) and would probably favour locally produced food if assured of its quality.

A wider issue is how consumers will respond if clearly offered the choice between cage-produced and RAS produced salmon. Although environmental lobby groups appear to be supporting RAS farming, it is clearly closer to "factory farming" than cage-based production with higher densities, smaller volumes for fish to swim in and less "natural" conditions. Whilst it might be tempting for both cage and RAS producers to seek to promote the benefits of their technology and seek to obtain a premium price over the other, the reality may be that salmon sales overall would be damaged as consumers would more easily pick up on the negative messages of both production methods. The major multiple retailers may also discourage differentiation on the basis of production system so as to maintain maximum flexibility on sourcing options.

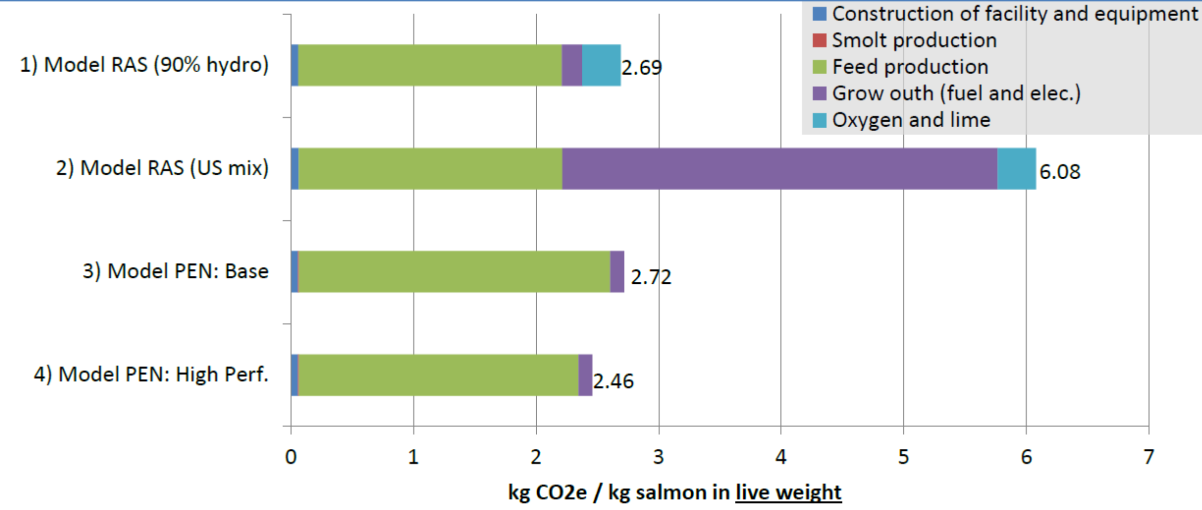
That said, under pressure from green lobby groups, especially in North America, supermarkets are developing sustainable seafood policies which could impact cage salmon production. The Overwaitea Food Group in Canada are substituting the amount of cage reared salmon available in their stores with as much closed-containment reared salmon as possible. Overwaitea Food Group came top of Greenpeace Sustainable Seafood Rankings in 2012 for its commitment and efforts in sourcing and selling sustainable seafood. The closed containment coho salmon producers in British Columbia and Washington are currently obtaining a significant price premium for their product by virtue of their ability to market it as an environmentally sustainable product. 'Namgis' farm has secured direct-to-market place contracts with grocers who verify the premium price at 25 to 30%. However, this is only for relatively small scale production and as RAS production grows these price premiums may diminish. If RAS Atlantic salmon production grows quickly and overseas markets also secure near market supplies through national based RAS production then it is inevitable that any premium price secured by RAS farmers in Europe during the early days of RAS development will come under pressure.

A student research project carried out in Canada (Yip, 2012) found consumers willing to pay an average premium of 3.9% for CCA (Closed Containment Aquaculture) produced salmon over conventional farmed sources. However, the same study found a willingness to pay an average of 9.8% for salmon from IMTA (Integrated Multitrophic Aquaculture) systems involving the use of marine cages. The same study found a substantial preference for wild over farmed salmon (64.6% compared with 4.2% preferring farmed salmon whilst 31% either had no strong preference or didn't know). However, when the benefits of IMTA and CCA were explained 44.3% of respondents preferred that adoption of IMTA compared with 16.3% preferring the adoption of CCA over conventional methods.

Furthermore, the sustainability of RAS farmed Atlantic salmon in contrast to cage production very much depends on the environmental criteria that are considered. Rosten et al. (2013) reported the greenhouse gas emissions (GHG) associated with various production criteria for both RAS and cage salmon (Figs. 20 & 21). Clearly, although the results are still based partly on assumptions, the source of power, location of production and final market destination for the RAS farmed product can have a significant impact on its sustainability profile.

Danish Salmon has clearly stated that it intends to export its first RAS salmon to the US, Canada and the EU which rather weakens the environmental credentials of the RAS farmed salmon. This perhaps explains why the company also intends to build farms in these countries such that they avoid the CO_2 emissions associated with air freight.

Figure 20: Carbon emissions per kg of salmon produced



Sum of GHG emissions caused by the production of one kilo of salmon in <u>live weight</u> from production of feed ingredients and up to salmon is ready for slaughter.

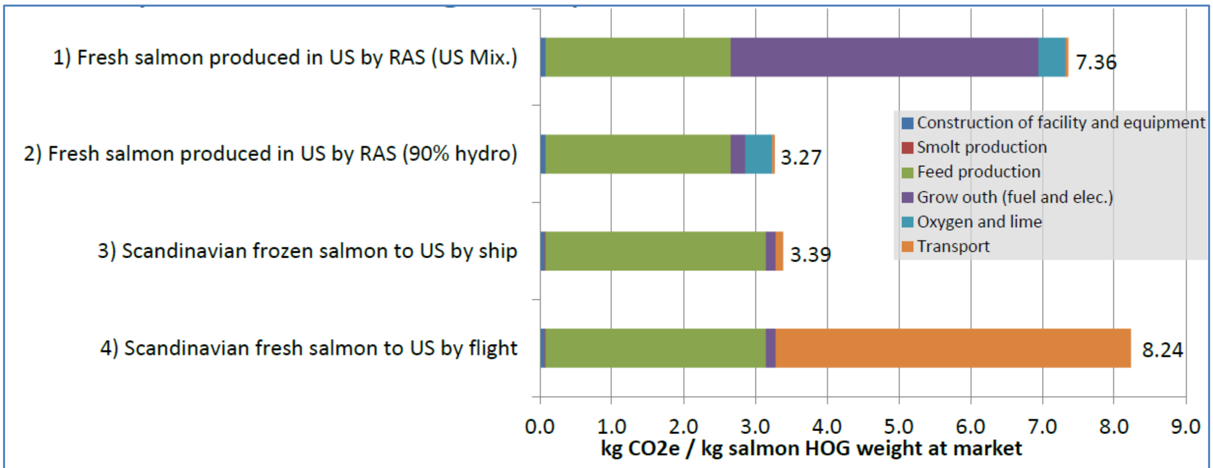
Cases:

1. Model RAS system using a 90% hydropower / 10% fossil fuel electric mix with a GWP of: 0,04 kg CO2e/kWh*
2. Model RAS system using an average electric mix for the US with a GWP of 0,77 kg CO2e/kWh*
3. Model Net pen system. Average FCR: 1,27
4. Model Net pen system with best practice, FCR: 1,14

*: Modelled with data from the EcoInvent v2.2 database

Source: Rosten et al., 2013.

Figure 21: Emissions associated with transport to retailers in the US



Sum of GHG emissions caused by the production and transport of one kilo of salmon in head on and gutted (HOG) weight (from production of feed ingredients and up to delivery at retailer gate)

Cases:

1. <u>Fresh</u> salmon from RAS system using an average US electricity mix and transported 500 km to retailer with <u>efficient truck</u>
2. <u>Fresh</u> salmon from RAS system using 90 % hydro power electricity mix and transported 500 km to retailer with <u>efficient truck</u>
3. <u>Frozen</u> salmon from PEN system in Norway transported 5 600 km to the west coast of the US by <u>large container ship</u>
4. <u>Fresh</u> salmon from PEN system in Norway transported 5 600 km to the west coast of the US by <u>airfreight</u>

Source: Rosten et al., 2013.

RAS production also assumes that the product will be of at least the same quality as cage salmon if not superior. Unfortunately, in the rush to make claims of the potential improved fish quality from RAS farms investors are not always fully aware of all the issues that need to be considered when operating RAS at commercial stocking density levels.

Certification

Third-party certification schemes provide an opportunity to enhance the credibility of environmental claims made by RAS operators. The Aquaculture Stewardship Council (ASC) has struggled to implement their salmon standards due to industry resistance to the requirement for closed-containment production of smolts. A confederation of the largest producers (accounting for 70% of global production) known as the Global Salmon Initiative (GSI) have negotiated a 5yrs transition period, but this will clearly provide a greater economic incentive for smolt RAS production going forward. Also, many standards are not necessary for RAS e.g. requirements for benthic monitoring required for cage grow out. CO_2 emissions is one the few areas where RAS environmental performance is worse than cage-production. However the ASC standards (and those of the other two largest certifiers; Global Aquaculture Alliance (GAA) and GLOBALGAP) stipulate that monitoring should be used to support continuous improvement – but no limits are stipulated. Although some organic standards permit RAS production of juveniles, it is highly unlikely that this possibility will be extended to grow-out production in RAS.

6.3 Economic impacts

In the short term (5-10 years) it might be the case that the development of RAS technology for salmon farming might be of economic benefit to Scotland if investment takes place here. Potential advantages of locating in Scotland at the present time might include:

- Ready access to juvenile stock (smolts)
- Access to established distribution networks for salmon
- Access to aquaculture expertise and supporting supply services
- Access to good quality fresh and seawater resources
- Lower land rates and labour rates than say SE England
- Potential for regional development funding support
- Potential use of the “Scottish brand”
- Access to renewable energy
- Within the EU

If Scotland becomes independent it is feasible that there will be a differential in prices of water and energy compared with England, with prices likely to be lower in Scotland. This could potentially be enough to offset the extra distance to major English markets. In any case, it is possible that the Scottish salmon industry will move towards the production of larger fish in RAS prior to shorter growout periods in larger and more offshore cage sites, resulting in increased RAS investment.

Whether RAS farms would substantially replace cage farms in Scotland is more doubtful. Taking an optimistic investment cost of £5,000 per tonne of production capacity; replacing the current Scottish production of salmon (162,223 tonnes in 2012) would require a capital investment of £811 million. There are few existing companies in the sector that could contemplate a rapid investment of this scale unless regulatory and market forces combined to make this necessary. Planning permission could also be an issue. Based on the Langsand Laks design an area of $4m^2$ per tonne of production capacity is required, which would translate to about 650,000 m^2 or 65 ha of building. For marine systems this will preferably be on coastal land to provide low cost access to clean seawater. A low elevation above sea level would generally be preferred to minimise pump cost for replacement water. However, with very high rate recycle systems this is a small contribution to total pump costs, so higher elevations e.g. to avoid potential flood risks would not be a major constraint.

For reasons already discussed, it seems likely that in the long term, most investment in RAS salmon aquaculture will take place closer to markets and/or processing capacity and hence probably outside Scotland. This could certainly limit Scottish export potential from existing cage farms, especially to more distant markets. The figure below illustrates the current patterns of global production and trade for salmon (albeit from a Norwegian perspective). This shows the major import markets to be Asia, Russia and the USA. If demand were to stay the same and regional supply increase in these countries, the greatest impact would probably be on Norway, as it is already a much larger supplier to these markets than Scotland. However, without an adjustment in production on the part of Norway, this would put further downward pressure on prices as the European Economic Area (but not the EU) has surplus salmon production. This would certainly affect Scottish producers. A further factor however, is that Norwegian companies are currently the largest shareholders in the Scottish salmon industry, so it is speculation whether they would wish to protect that as a strategic investment, or whether they might start to divest themselves of that investment.

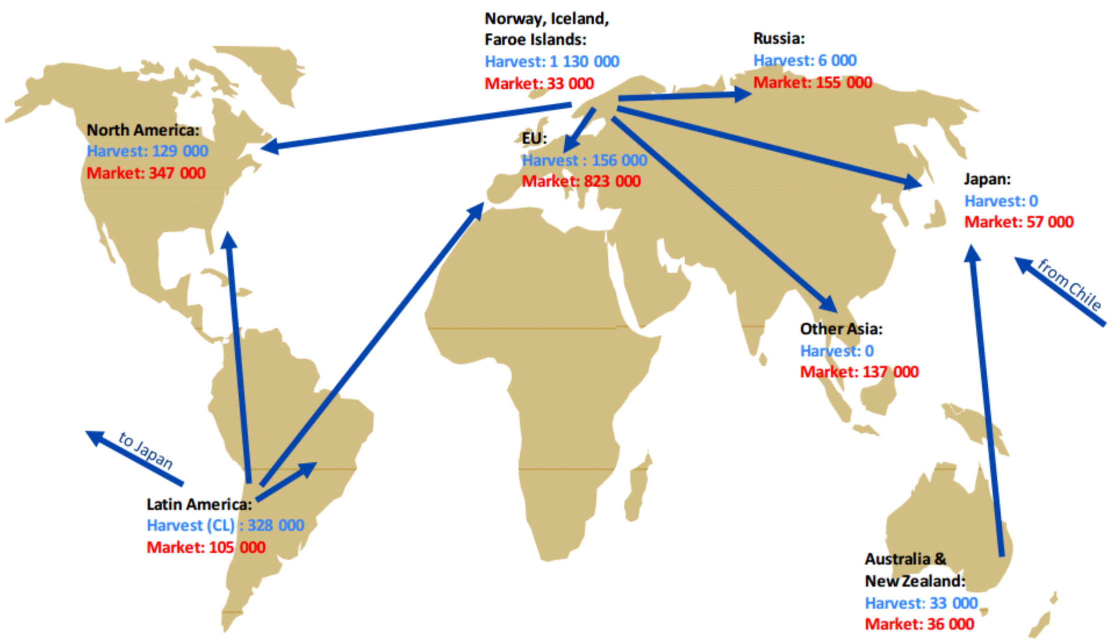


Figure 22: Global salmon markets and trade flows. Source: Marine Harvest, Salmon Farming Industry Handbook 2013[53] (Data from Kontali Analyse)

The largest market for Scottish producers is the UK at around 60,000 tonnes per annum. However, around 60% is exported to other European countries and further afield. Data from the Scottish Salmon Producers' Organisation (Table below), shows that the most important export markets are the USA (46% of exports in 2011) and France (23% of exports in 2011).

With the current level of interest and investment activity in salmon RAS in the USA, the development of this sector there could have a significant impact on Scottish salmon exports, particularly if it is perceived as "greener" than cage-based production. However, the increase in exports to the USA in 2011 was probably more associated with reductions in exports from Chile than due to a decision by North American consumers to choose Scottish salmon. As Chile recovers from severe problems with ISA and increases investment in

[53]marineharvest.com/PageFiles/1296/2013%20Salmon%20Handbook%2027-04-13.pdf

efficient production capacity, the North American market will probably become more competitive again in the relatively near future.

Table 11: UK (Scottish) salmon exports 2010 and 2011

UK FRESH SALMON EXPORTS				
	2011	2010	% INCREASE	% TOTAL
USA	43,703.71	31,924.22	37	46
FRANCE	21,699.73	26,475.78	-18	23
E.EUROPE	8,110.42	4,869.24	67	8
EIRE	5,869.20	4,509.20	30	6
CHINA	4,942.21	11.06	44569	5
GERMANY	2,152.01	2,458.38	-12	2
MIDDLE EAST	1,614.66	1,300.39	24	2
TAIWAN	929.31	83.49	1013	1
JAPAN	907.50	587.56	54	1
CANADA	749.86	1,111.22	-33	1
ITALY	562.88	456.79	23	1
SPAIN	474.41	209.81	126	0
OTHER	3,974.56	4,575.32	-13	4
TOTAL	**95,637.53**	**78,611.67**	22	**100**

Source: Scottish Salmon Producers Organisation[54]

Exports to Asia have been relatively small, but a political agreement in early 2011[55] led to several Scottish salmon products being awarded AQSIQ[56] certificates allowing them to be imported to China. This led to an increase in exports to China from 11 tonnes in 2010 to 4,942 tonnes in 2011 and reached 8,675 tonnes in the first 10 months of 2012[57]. It is the expectation of the Scottish Government and the industry that this can be further increased. In the long term, the development of RAS salmon farming in China could substantially limit the scope for Scottish exports. However, as China is such a substantial potential market, it is also likely that some market will remain for Scottish products providing a premium brand image can be retained.

The development of RAS salmon production in continental Europe (particularly France) would be a threat to Scottish salmon producers (although arguably more to Norwegian producers). Assuming production methods do not allow a significant overall premium for either approach, then prospects depend very much on the relative costs of production and distribution which could be significantly different in ten or twenty years' time. If RAS production becomes the most economic approach then within the UK, it might be expected that centres of production would develop around major processing and distribution hubs such as Humberside, or other strategic locations with large accessible markets.

The Scottish Government has commissioned a study to examine the current and future economic value of the Scottish aquaculture sector which is due to report shortly. Indicators of current value include the farmgate value of production which was £548.7 million in 2012[58], estimated to be worth over £1 billion at retail[59].

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[54] http://www.scottishsalmon.co.uk/
[55] http://www.scotland.gov.uk/News/Releases/2011/01/12082252
[56] General Administration of Quality Supervision, Inspection and Quarantine
[57] http://www.scottishsalmon.co.uk/media/news/2013/far_east.aspx
[58] http://www.scotland.gov.uk/News/Releases/2012/09/salmonproduction10092012
[59] http://www.scottishsalmon.co.uk/facts_figures/index.aspx

Expenditure by the industry on local goods and services was estimated to be £212 million in 2010/11[60]. The number of people directly employed in salmon farming is around 2200 with a further 6,200 jobs reliant on salmon farming within the wider economy[61]. Some of these numbers might be expected to increase if the salmon industry's current expansion continues. However, cost-competitive growth elsewhere might also be expected to increasingly impact and lead at least to the loss of some of this economic activity.

[60]http://www.scottishsalmon.co.uk/facts_figures/economic_value.aspx
[61]http://www.scottishsalmon.co.uk/facts_figures/index.aspx

7 Conclusions

7.1 Summary of findings

Although RAS technology has been in use for over 30 years, is still at a relatively early stage of development with respect to large-scale commercial grow-out, particularly of marine species. However, the potential of this approach continues to attract investment and technology is gradually improving. The salmon farming industry is increasingly adopting RAS for smolt production such that within the next 5 years almost all commercial growout will be reliant on smolts from RAS farms. This investment and build-up of expertise in RAS is likely to lead to the extension of the land-based freshwater stage to produce (approximately) 1 kg juveniles for stocking to sea cages. Whilst the industry will not wish to rush into this investment, it could be a logical step if the technology proves reliable and cost effective as it would shorten the growout time at sea and make the use of more offshore sites feasible. Factors might include lower exposure to diseases risk, avoidance of the need to change nets on large cages during growout, shorter overall production cycles, greater flexibility with respect to site fallowing, and an overall improvement in feed conversion efficiency. It would also help address environmental and conservation concerns which are most focused on the use of inshore sites in the path of salmon migrations or for instance, near to seal haul outs or sensitive marine habitats. Fewer but larger offshore sites would also enable the industry to increase operational efficiency and capitalise on scale economies.

At the present time, successful and economically competitive RAS farms for salmon growout look some way off and will require further technology development. Business plans that rely on product achieving premium prices or operating at planned capacity without major incident in the first two years should be treated with caution given the long history of failed projects in this area. There are potential game-changers with respect to technology. For instance, if genetically modified salmon are accepted by the market and duly authorised but only for production in RAS. If the performance of such fish were substantially better than selectively bred strains used in the cage sector, then an economic advantage might be seen. However, this is considered unlikely at least in the near term.

In the short term, RAS for salmon production is most likely to be cost effective close to markets where premium prices can be obtained for very fresh (or even live) product. This includes parts of Asia, possibly Gulf States and perhaps places in North America. If RAS production becomes cost competitive with cage production then more substantial growth in this area might be seen closer to key markets and distribution hubs. In the long term this could have an impact on the Scottish production sector as overall competition will increase.

If RAS technology improves to enable the production of salmon closer to overseas markets, it would also enable the production of a wider range of species in Scotland. A range of potential species have been identified in Section 5.1. Since the Scottish market is relatively small, it is unlikely that a substantial industry could develop for any of these species. However, there might be scope for a limited number of projects. These could be competing with RAS projects in England, which would have the benefit of being closer to larger markets. On the other hand, Scotland may be able to offer lower prices on (especially renewable) energy and water. For the near to medium term it seems likely that lower-cost production overseas (especially the potential for developments in Latin America and Africa) will provide strong competition for UK-based RAS. However, in the longer-term, increasing demand for high quality fish in Asia particularly, might discourage exports and reduce competition for UK/EU producers.

Key findings from this study include:

- RAS technology is well developed in the freshwater and marine sectors specifically for hatcheries supplying fingerlings to net pen farms for grow out.

- Table-fish RAS remain far more sensitive to market prices and rising (feed and energy) input costs than conventional production systems. However, despite a poor track record for lenders, selected case studies suggest an improved outlook for longer-term economic sustainability potential.

- Unit production costs are higher for saltwater than freshwater systems, though market prices are also higher in most cases.

- Some RAS technology suppliers continue to avoid highlighting the outstanding technical and economic issues relating to the performance of RAS leaving the investor to embark on a road of discovery.

- RAS technology for land based fattening farms to produce market size fish is more advanced in the freshwater sector although success with species such as eel, tilapia and even salmon smolts is not an indication of appropriate technology for grow out production.

- RAS technology has demonstrated the advantages of fish production under controlled environmental conditions in terms of fish quality, superior growth rates and feed conversion ratios, reduced disease outbreaks, lower use of therapeutants and site flexibility.

- While several RAS technology suppliers claim to have constructed a number of marine RAS farms it remains that globally there are very few such farms that exceed 200 tonnes production per annum and where the system is over 90% recirculation i.e. representing a definition of RAS farm technology which enables close environmental control of all water quality parameters.

- It remains that for commercial fattening scale RAS farms in excess of 500 tonnes pa the economic viability is yet to be proven in either the marine or freshwater sectors.

- Economic projections of commercial RAS profitability and production costs based on small pilot research projects and desk studies give limited guidance to the viability of financial investment in commercial scale RAS technology for different species, markets, countries and location.

- To be profitable RAS farmers must target higher premium market segments as part of their market-mix, and seek to exploit appropriate scale economies. However, the potential for saturation of relatively small niche premium markets suggests that there may be a contradiction between this strategy and the scale-economy strategies of current start-ups

- RAS production of salmon or any other seafood species should be based on hard economic analysis that takes into account the environmental, socio-economic and production costs using different farming systems.

- A range of credible sustainability attributes linked to RAS production can be used to differentiate RAS from 'open' production systems.

- Environmental drivers for RAS production should take into account credible Life Cycle Analysis assessment of the different seafood production methods including all aspects of cage and RAS production.

- The argument of RAS sustainability over cage production should be defined by a range of criteria including efficiencies of feed utilisation, energy source, target species, actual ability of the RAS farm to avoid disease and parasite transmission to recipient waters and the distance and mode of transport to market for final product.

- According to management of a RAS farm, its design and standard of RAS technology they can remain exposed to infestation by parasitic organisms.

- Europe has the most active programme of research into RAS technology but there remain several areas where the technology requires improvement in terms of effectiveness and operating costs.

- The UK presents a business challenge to successfully farm any species using RAS technology where the target species faces market competition from mass production of that species using low cost production methods, sustainable supplies from the capture fishery or imported product.

- The first European RAS farmed salmon to be delivered to market had a 20-30% higher production cost compared to the most efficient cage farm in Norway.

- The USA, which relies almost entirely on imports to meet its demand for salmon, also has one of the largest markets for premium seafood products. China and SE Asia also represent important emergent markets. Recent European salmon and sea bass RAS start-ups are already targeting these markets and this is central to their business plans. Based on our economic analysis there is some risk that these ventures may ultimately serve as incubation projects for establishment of local co-located RAS sectors that could provide high value fresh products to these markets. This will preclude the need for costly and environmentally sensitive air freighting.

- A further potentially significant threat to the establishment of a Scottish RAS table-fish sector is associated with the on-going attempt to license a fast-growing transgenic Atlantic strain in the USA. European consumer antipathy to GMO's means this could hand a significant comparative advantage to a co-located RAS sector in the United States.

In summary, RAS technology is developing and is commercially viable for high unit value species or life stages (e.g. juveniles), or to some extent for lower value species that can be reared at high density in less demanding water quality conditions. The economic bar to the use of RAS will gradually be lowered as technology improves and scale economies are realised. The use of RAS technology is already increasing in the Scottish salmon industry and further investment in this area will almost certainly be essential for the successful future of the industry. There is a long-term threat to the industry from RAS technology being adopted closer to major markets, but this should be seen as an incentive to continue to innovate for cost competitiveness using the natural resources available in Scotland.

7.2 Recommendations

There should be no presumption against RAS technology as it is likely to play an important role in the future development of the Scottish salmon industry and in the future provide some further opportunities for small to medium sized enterprises.

A policy that strongly favours RAS farms to the detriment of cage farms would be likely to damage the Scottish industry unless strong incentives can be introduced to attract local investment rather than location closer to end markets

RAS technology is still at an early stage of development, so any projects proposing commercial grow-out for low value commodity species facing competition from lower cost production methods should be considered very high risk.

Any public funding of RAS projects should include detailed scrutiny of plans by a multidisciplinary team of independent (and appropriately experienced) experts.

There should be a mechanism in place for RAS projects that have public funding and which subsequently fail to lodge full details of lessons learned in a publicly accessible database.

Support for research and pilot-scale projects should be encouraged.

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Annex 1: Example RAS Technology Suppliers

AquaSystems UK Ltd (UK – Scotland)	http://www.aquasystems.co.uk/
International Aqua-Tech (UK – Wales)	http://www.iat.uk.com/
Llyn Aquaculture (Wales)	http://www.llyn-aquaculture.co.uk/
Billund Aquaculture (Denmark)	http://www.billund-aqua.dk/
Aquatec Solutions (Denmark)	http://aquatec-solutions.com/
Inter Aqua Advance (Denmark)	http://www.interaqua.dk/
Krùger Kaldnes	http://www.krugerkaldnes.no/
OCEA (ex-Hydrogest) (Norway)	http://www.ocea.no/
AKVA Group (Norway/Denmark)	http://www.akvagroup.com/
Akvaplan Niva	http://www.akvaplan.niva.no/
Hesy Aquaculture (Netherlands)	http://www.hesy.com/
Aqua EcoSystems (Netherlands)	http://www.aqua-ecosystems.com/
Aquacultur Fischtechnik GmbH (EMF) (Germany)	http://www.aquacultur.de/
Aquabiotech (Malta)	http://www.aquabt.com/
Grow Fish Anywhere (Israel)	http://growfishanywhere.com/
Holder Timmons Engineering (North America)	http://www.holdertimmons.com/
AquaCulture Enterprises (USA)	http://www.aquacultureenterprises.com/
PRAqua (Canada)	http://www.praqua.com/
Atlantech Companies (Canada)	http://www.atlantech.ca/
INACUI S.A. (Chile)	
Cell Aquaculture (Australia & Malaysia)	http://www.cellaquaculture.com.au/

NB: This list is intended to illustrate the range of technology supply companies active in recirculated aquaculture. Inclusion in the list in no way implies endorsement of the company by the report authors and equally, omission of any company does not imply any adverse opinion of them.

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