Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (*Salmo salar*): Land-based closed containment system in freshwater and open net pen in seawater

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**A B S T R A C T**

Ocean net pen production of Atlantic salmon is approaching 2 million metric tons (MT) annually and has proven to be cost- and energy-efficient. Recently, with technology improvements, freshwater aquaculture of Atlantic salmon from eggs to harvestable size of 4–5 kg in land-based closed containment (LBCC) water recirculating aquaculture systems (RAS) has been demonstrated as a viable production technology. Land-based, closed containment water recirculating aquaculture systems technology offers the ability to fully control the rearing environment and provides flexibility in locating a production facility close to the market and on sites where cost of land and power are competitive. This flexibility offers distinct advantages over Atlantic salmon produced in open net pen systems, which is dependent on access to suitable coastal waters and a relatively long transport distance to supply the US market. Consequently, in this paper we present an analysis of the investment needed, the production cost, the profitability and the carbon footprint of producing 3300 MT of head-on gutted (HOG) Atlantic salmon from eggs to US market (wholesale) using two different production systems—LBCC-RAS technology and open net pen (ONP) technology using enterprise budget analysis and carbon footprint with the LCA method. In our analysis we compare the traditional open net pen production system in Norway and a model freshwater LBCC-RAS facility in the US. The model ONP is small compared to the most ONP systems in Norway, but the LBCC-RAS is large compared to any existing LBCC-RAS for Atlantic salmon. The results need to be interpreted with this in mind. Results of the financial analysis indicate that the total production costs for two systems are relatively similar, with LBCC-RAS only 10% higher than the ONP system on a head-on gutted basis (5.60 US$/kg versus 5.08 US$/kg, respectively). Without interest and depreciation, the two production systems have an almost equal operating cost (4.30 US$/kg for ONP versus 4.37 US$/kg for LBCC-RAS). Capital costs of the two systems are not similar for the same 3300 MT of head-on gutted salmon. The capital cost of the LBCC-RAS model system is approximately 54,000,000 US$ and the capital cost of the ONP system is approximately 30,000,000 US$, a difference of 80%. However, the LBCC-RAS model system selling salmon at a 30% price premium is comparatively as profitable as the ONP model system (profit margin of 18% versus 24%, respectively), even though its 15-year net present value is negative and its return on investment is lower than ONP system (9% versus 18%, respectively).

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**Abbreviations:** CO₂, carbon dioxide; CO₂ eq, carbon dioxide equivalents; EBIT, earnings before interest and taxes; FCR, feed conversion ratio; HOG, head-on gutted; IRR, internal rate of return; LBCC, land-based closed containment; LCA, life cycle assessment; NPV, net present value; ONP, open net pen; RAS, recirculating aquaculture system; ROR, required rate of return; S0, 1/2-year old smolt; S1, 1-year old smolt; TGC, thermal growth coefficient; tkm, ton × kilometers; WFE, whole fish equivalent.

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The results of the carbon footprint analysis confirmed that production of feed is the dominating climate aspect for both production methods, but also showed that energy source and transport methods are important. It was shown that fresh salmon produced in LBCC-RAS systems close to a US market that use an average US electricity mix have a much lower carbon footprint than fresh salmon produced in Norway in ONP systems shipped to the same market by airfreight, 7.41 versus 15.22 kg CO₂eq/kg salmon HOG, respectively. When comparing the carbon footprint of production-only, the LBCC-RAS-produced salmon has a carbon footprint that is double that of the ONP-produced salmon, 7.01 versus 3.39 kg CO₂eq/kg salmon live-weight, respectively.

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1. Introduction

Farmed Atlantic salmon (Salmo salar) is sold globally in various forms and markets. The US is an important market for farmed Atlantic salmon, estimated to be more than 350,000 MT in 2014 (Marine Harvest ASA, 2014), and has shown steady growth since the late 1980s (USDA ERS, 2015). In 2014 the US market was primarily supplied by salmon produced in Chile (126,820 MT), Canada (47,454 MT) and Norway (26,208 MT) (USDA ERS, 2015). The US production of Atlantic salmon (18,000 MT [2012]) is relatively small in comparison to the amount consumed in the US (NOAA, 2013).

Limited access to suitable coastal water areas and rigorous regulations in the US (NOAA, 2013) curtail the opportunity to produce Atlantic salmon in open net pen systems, the industry’s preferred and established technology for the on-growing phase of salmon farming in Norway, Canada, and Chile. An alternative technology to open net pen systems for salmon production is land-based, closed containment (LBCC) water recirculating aquaculture systems (RAS) technology (LBCC-RAS). LBCC-RAS technology had been used for production of a limited number of species, like eel, beginning in the 1980s (Heinsbroek and Kamstra, 1990). Developments in LBCC-RAS technology since the 1980s have led to the ability to culture a wide variety of fish species including cold-water salmonids (e.g., Arctic char, rainbow trout, and Atlantic salmon to smolt size) (Summerfelt et al., 2004; Bergeheim et al., 2009; Dalsgaard et al., 2013; Kolarevic et al., 2014). Most recently, freshwater aquaculture of Atlantic salmon from eggs to harvestable size of 4–5 kg in a LBCC-RAS facility has been demonstrated as a viable production technology (Summerfelt et al., 2013). Land-based, closed containment water recirculating aquaculture systems technology offers the ability to fully control the rearing environment, exclude parasites and obligate pathogens, and provide flexibility in locating a production facility close to the market and on sites where the cost of land and power are competitive. This control and flexibility offers advantages over Atlantic salmon produced in open net pen systems (ONP), which is negatively impacted by sea lice and dependent on access to suitable coastal waters and a relatively long transport distance to supply the US market. Interest in production of Atlantic salmon using LBCC-RAS technology has led to construction of a number of commercial LBCC-RAS farms (Summerfelt and Christianson, 2014). Although their current supply to the US Atlantic salmon market is just beginning, plans for a number of US-based LBCC-RAS farms for Atlantic salmon have been reported in the trade press. It is therefore of particular interest to compare such different approaches for production of the same seafood to the same market.

The aquaculture production of Atlantic salmon has been estimated to exceed 1,900,000 MT in 2014; global production has increased 428% since 1994 (Marine Harvest ASA, 2014). Open net pen farming in the ocean has been the major technology for the on-growing portion of the production cycle. The technology for ONP farming with large net pen volumes, exceeding 60,000 m³ in one pen, has proven to be cost- and energy-efficient (Ziegler et al., 2013), leading to commercial success and founding a large global business. However, the growth of the industry has not been without environmental conflicts, especially towards wild Atlantic salmon and Sea Trout (Salmo Trutta) where negative impacts on wild populations due to escapees have been suggested (Naylor et al., 2005). Alternative methods for growing salmon in closed containment systems for the whole production cycle have been attempted since the beginning of the 1990s, with no commercial success, either land-based or in floating bags (Liu and Sumaila, 2007). Recently, a new interest for producing Atlantic salmon in closed containment systems has arisen (Summerfelt and Christiansen, 2014). A variety of closed containment systems are being suggested (Rosten et al., 2013), but LBCC-RAS technology seems to have found a particular global interest, with LBCC-RAS farms being planned, built and put into production in Europe, North America, China, and Norway (Summerfelt and Christianson, 2014).

Norwegian-farmed Atlantic salmon is sold as fresh, frozen, filleted, smoked and cured product. Fresh whole salmon is the primary product and accounts for approximately three quarters of the total value of exports (Statistics Norway, 2015). Fresh salmon has the highest export price. Denmark, France and Japan are the biggest export countries, making up of one-third of total Norwegian salmon exports (Statistics Norway, 2015). Norwegian salmon made up approximately 8% of the US salmon market in 2014 (USDA ERS, 2015).

The production cost of Atlantic salmon farming in Norway has been charted annually since 1986. From 2008–2012 the production cost has varied between 21.04 and 22.98 NOK per kilo WFE (Directorate of Fisheries, 2014). It has recently increased due to the high cost of sea lice treatment (Liu and Bjelland, 2014). The relatively low investment cost for open net pen production sites compared to the investment cost for proposed LBCC-RAS farms has historically favored open net pen production. Norway has the lowest production cost per kilo of salmon compared to Canada, Great Britain and Chile due to economies of scale (Marine Harvest ASA, 2014).

The economic viability of intensive LBCC-RAS has been evaluated (Muir, 1981; Gempeasaw et al., 1993; Losordo and Westerman, 1994; De Ianno et al., 2006; Timmons and Ebeling, 2010), though these studies have largely focused on specific system designs for a single level of output, and have not identified the capital and operating cost savings which may exist as water treatment processes are optimized and as technologies are scaled appropriately. De Ianno et al. (2006) reported that increasing LBCC-RAS facility capacity, increasing sale price, and decreasing facility capital cost were the most important factors affecting economic viability. These savings can be significant and can contribute to the success or failure of an aquaculture business employing this type of technology.

Environmental assessments of ONP salmon production and distribution have identified feed production as a dominating climate aspect of salmon aquaculture production, closely followed by transportation of the salmon to retailer (Ziegler et al., 2013). A shift into more closed systems includes changes such as: replacing ocean
current energy with electricity; more alternative materials in the production facilities; controlling interactions with the surrounding environment; collecting and utilizing nutrients in the biosolids produced by the fish; and placing the production close to the market or independent of oceans. There are several potential environmental tradeoffs in this shift. Feed efficiency is especially important, but also the balance between an increase in energy use in the growout phase versus a reduction in transport distance.

This paper aims to investigate whether domestic US production of Atlantic salmon in a LBCC-RAS farm is competitive when compared to a similarly sized ONP system overseas, using investor relevant keys like return of investment, production cost, market price, and carbon footprint. In this paper we present an analysis of the investment needed, the production cost, the profitability and carbon footprint of Atlantic salmon farming from eggs to US market (wholesale) using two different production systems—LBCC-RAS technology and ONP technology using enterprise budget analysis and calculating the carbon footprint with the LCA method. In our analysis we compare the traditional ONP production system in Norway and a model freshwater LBCC-RAS facility in the US. We model the necessary product prices to obtain profitability with LBCC-RAS, and compare the profitability to a similarly-scaled ONP system and provide a sensitivity analysis for the most important impact factors. In addition, we incorporate a comparison of the carbon footprint of the two systems using an overview of the consumed materials, feed, energy, transport and energy source.

2. Materials and methods

The feasibility of two commercial-scale farming systems for Atlantic salmon, a LBCC-RAS farm in the US and an ONP farm in Norway, is evaluated through a concept-level design and capital and operational cost analysis for 3300 MT head-on gutted (HOG) production systems. The economic performance is evaluated in detail using an enterprise budget analysis, while the environmental performance is evaluated in detail using attributional life cycle analysis. The ONP system evaluated here was scaled down from the more common large-sized facilities in Norway to fit to the comparable LBCC-RAS system.

2.1. Open net pen system model

Technical design of the ONP model farm is based upon a biological production plan (i.e., bioplan), data and operational practices obtained from Norwegian salmon farmers. Data and specifications of components are gathered from aquaculture industry suppliers in Norway. The ONP model farm includes concept-level design of floating rings, nets, mooring systems, boats, feed barge systems, camera systems, feed distribution systems and remote power systems. The bioplan, which predicted fish growth and size from smolt to harvestable size, results in two active growout sites, using limitations for fish density of 25 kg/m³ and maximum allowable biomass of 200,000 fish per unit.

The bioplan for the 3300 MT ONP model farm is based upon average ambient sea temperatures from mid-Norway, stocking with two smolt cohorts per year. The ONP system is assumed to stock a cohort of 1 m smolts, average size 100 g, on April 1 and a cohort of 2.5 m smolts, average size 7.5 g, on August 1. Fish growth and associated feed demand are determined by using specific growth rates (SGR) and feed conversion ratios (FCR) given in feed supplier feeding tables for various fish sizes. Fish growth estimates are reduced by 12% to compensate for handling and treatment of the fish during the production cycle. The overall FCR was set to 1.27 to obtain the average FCR from the last 10 years in Norway (Directorate of Fisheries, 2014). Mortalities for smolt to harvest are set to obtain 16% per generation mortality to comply with a dataset available from mid-Norway (Mattilsynet, 2011).

2.2. Land-based closed containment recirculating aquaculture system model

Technical design of the LBCC-RAS model farm is based on data developed by The Conservation Fund’s Freshwater Institute growout trials of Atlantic salmon, some of which has been reported (Summerfelt et al., 2013). This includes concept-level water recirculation system designs for each fish group developing in the bioplan. Each water recirculation system design includes multiple recirculation modules to allow for staging and movement of fish throughout the facility. Concept designs for incubation, fry, smolt, pre-growout, and growout rearing areas, as well as a final purging system, are completed using steady-state mass balance analyses. Design water quality criteria used in the mass balance analyses are based on the Conservation Fund’s Freshwater Institute growout trials. Growth rate coefficients (TGC) are used to predict fish growth for the bioplan for the 3300 MT LBCC-RAS model farm. Thermal growth rate coefficients are based on data collected in growout trial data from The Conservation Fund’s Freshwater Institute. Additionally FCR, mortality, head-on gutted yield, and other performance indicators, which are used to develop a biological plan are taken from past growout trials (Summerfelt et al., 2013). The FCR (kg/kg) and TGC (1000 g1/3/°C days) are set to vary according to these growout trial data at different life stages; FCR: Fry: 0.75; smolt, 0.90; pre-growout, 1.0; growout 1.1; and TGC: Fry: 1.25; smolt, 1.40; pre-growout, 2.0; growout, 2.30. The overall average FCR based on the individual values is 1.09. A maximum biomass density of 80 kg/m³ is used for the biological plan of the LBCC-RAS model farm.

The steady-state feed requirement for the LBCC-RAS model farm is 11,815 kg/day. Water supply required for the entire 3300 MT LBCC-RAS model farm is based on allowing no more than 75 mg/L nitrate-nitrogen at maximum loading in each recirculation system, assuming no passive denitrification within the systems. The

### Table 1

| Fish Rearing Area | Modules | Units per module | Unit diameter by depth (m x m) | Total Rearing Volume (m³) | Module Flow Rate (m³/min) | Total Flow Rate (m³/min) | Total Makeup Flow Rate (m³/min) | Maximum Module Feed Rate (kg/day) |
|------------------|---------|------------------|-------------------------------|--------------------------|--------------------------|---------------------------|---------------------------------|----------------------------------|
| LBCC-RAS—fry    | 1       | 18               | 2 by 1.0                      | 57                       | 1.5                      | 1.5                       | 0.08                            | 22.9                             |
| LBCC-RAS—smolt  | 2       | 4                | 9 by 2.0                      | 1,018                    | 11.4                     | 22.7                      | 0.19                            | 248.0                            |
| LBCC-RAS—pre-growout | 3 | 4               | 10 by 3.0                     | 2,827                    | 22                       | 66                        | 0.57                            | 549.5                            |
| LBCC-RAS—growout | 8      | 5                | 16 by 4.25                    | 34,180                   | 95                       | 757                       | 5.75                            | 2063.5                           |
| LBCC-RAS—final purging | 1 | 2               | 16 by 4.25                    | 1,709                    | 38                       | 38                        | 1.1                             | –                                |
| ONP—System*     | 2       | 6                | 157 by 40                     | 587,000                  | –                        | –                         | –                               | –                                |

*The ONP system is a growout system from smolts to harvestable size. Smolts and harvest/packing of the salmon are modeled to be provided by subcontractors.

b The water exchange in the ONP system is dependent upon water current and conditions of the nets (mesh size and fouling).
amount of water supply needed to maintain this nitrate-nitrogen level in the recirculation systems is calculated to be 7.7 m³/min, including 1.1 m³/min for finishing/purging the harvested salmon before slaughter. The resulting water required per feed fed is 803 L/kg for the systems that have feeding fish, i.e., all RAS except the purge system. The power requirement for the model farm is 2458 kW, comprised primarily of power required for the water recirculation pumps (2079 kW); the total power required per unit of live weight salmon produced is 5.4 kWh/kg (4.6 kWh/kg for pumping only).

Concept-level design characteristics for each rearing area in both production systems are summarized in Table 1; the inputs required for the two systems are summarized in Table 2; illustrative renderings are shown in Fig. 1. The technical design for each model farm allowed the progression of capital and operating costs for comparison of the two production systems. Cost data used in the development of the concept-level estimates provided here is a combination of industry standard published cost data (Directorate of Fisheries, 2014; Marine Harvest ASA, 2014; RS Means, 2010) and project specific vendor quotations obtained in 2010–2011.

**Table 2**

| Input factors                  | ONP system | LBCC-RAS system |
|-------------------------------|------------|-----------------|
| Feed (US$/kg)                 | 1.48       | 1.50            |
| Farm labor (# person)         | 6          | 10              |
| Farm labor (US$/person/year) | 125,000    | 45,000          |
| Processing labor (# person)   | –          | 6               |
| Processing labor (US$/person/year) | 0.38/kg | 37,500 |
| Livestock (US$/smolt or US$/egg) | 1.53 | 0.30 |
| Electric (US$/kWh)            | 0.17       | 0.05            |
| Oxygen (US$/kg)               | –          | 0.20            |
| Wellboat cost (US$/kg⁴)       | 0.92       | –               |
| Bicarbonate (US$/kg)          | –          | 0.35            |
| Management (US$/year)         | –          | 500,000         |
| Other operating cost          | 0.43 US$/kg fish | – |
| Insurance (US$/kg⁵)           | 0.02       | 0.02³          |
| Tax level                     | 28%        | 28%             |
| Equity ratio                  | 30%        | 40%             |
| Interest loans                | 3.0%       | 6.0%            |

³ Whole fish weight.

⁴ First year is 0.04 US$/kg.

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Fig. 1. Concept-level renderings of the growout rearing area in a 3300 MT HOG Atlantic salmon LBCC-RAS farm (A) and ONP farm (B).
2.3. Economics

Salmon aquaculture is a commercial operation whose purpose to be profitable. The prerequisite for a business to be sustainable is to be profitable in both the short- and long-term and over the investment horizon. The financial performance of these two aquaculture production systems is investigated using an enterprise budget analysis; this allows an assessment of the feasibility and profitability of the two systems. Enterprise budgets, also called production budgets, provide a framework within which all the components of costs and revenues associated with the production of farm products are itemized. The budget is constructed on a production basis, and the assessment is built upon a cash flow analysis. The profitability is calculated based on financial statements such as income statement and balance sheets.

There are a number of well-developed analytical techniques for analyzing profitability (Liu and Sumaila, 2007; Kumar and Engle, 2011). Net present value (NPV) is a commonly used parameter to provide an objective decision of an investment and project. Net present value takes into account the time value of money, and is the difference between the present value of total costs and total revenue over an operational horizon. Positive NPV indicates that an investment is worthwhile. In addition to NPV, other indicators are also used as assessment criteria; these include gross margin, return on investment (ROI), internal rate of return (IRR), payback period, and break-even production and price. Gross margin is expressed as revenue minus variable costs; net income or profit is revenue minus all costs. Return on investment is the rate of return on the initial capital investment and is estimated by profit before taxes divided by the capital investment. Internal rate of return is the discount rate at which net present value of profit is set equal to zero. Breakeven analysis can inform the conditions necessary for the business to become profitable or to remain in business.

2.3.1. Enterprise budget

The enterprise budget is estimated based on a total production of 4000 MT wet weight, which is equivalent to 3300 MT of head-on gutted weight. Head-on gutted yield is estimated to be 88% after a 5% loss of weight during final purging for both the ONP and the LBCC-RAS production systems. The estimates of total investment cost and operating cost of each cost item are based on the production system design models and their associated bioplans. The costs include two parts: capital cost and operating cost.

2.3.2. Capital cost—ONP model

Capital costs incur at the beginning of the operation, and most of these costs are one-time costs. The capital cost for the 3300 MT ONP model farm is based on information gathered from the Norwegian aquaculture industry, and is thereby considered representative for an ONP farm constructed and operated according to Norwegian laws and regulations (Norway, 2008). The ONP model farm includes 3 licenses and 12 pens, and their associated physical components consisting of floating rings, nets, mooring systems, boats, feed barge systems, camera systems, feed distribution systems and remote power systems. The cost of each item is estimated based on current market price suppliers’ command. Compared to estimates reported by Marine Harvest (Marine Harvest ASA, 2014), the capital cost for the ONP model farm is considered representative for a two site ONP farm. We assume that the lifespan of nets and feeding system is 5 years, floating rings is 8 years, camera and power systems is 10 years, and the remainder of the equipment is 20 years. These lifespans are used for calculation of depreciation and replacement cost.

### Table 3

| Table 3 | Capital expenses for a 3,300 MT HOG LBCC-RAS and ONP Atlantic salmon farm. |
|---------|--------------------------------------------------------------------------------|
| **ONP system cost components** | **Cost (US$)** |
| Licences | 23,571,429 |
| Floating rings | 1,834,286 |
| Nets | 857,143 |
| Moorings | 342,857 |
| Boats | 1,285,714 |
| Feed barges | 1,371,429 |
| Camera systems | 214,286 |
| Feed distributors | 34,114 |
| Power systems | 188,571 |
| Total | 29,699,829 |
| **LBCC-RAS system cost components** | **Cost (US$)** |
| RAS Systems | 26,640,557 |
| Effluent treatment | 3,487,500 |
| Water supply | 675,000 |
| Processing | 2,112,030 |
| Building | 9,426,413 |
| Engineering | 5,080,980 |
| Construction management | 1,058,938 |
| Bond | 254,049 |
| Contingency (10%) | 4,848,102 |
| Total | 53,583,169 |

The cost for an ONP farming license in Norway is included in the capital cost estimate for the ONP model farm. The current cost of ONP farming licenses is much higher when compared to license costs of the 1990s (Färe et al., 2005); cost for a license in the current open market is approximately 55 million Norwegian kroners, which is equivalent to 8 million US dollars (Aardal, 2014). The total capital cost of the ONP model farm including licenses at current prices is estimated to be 29.7 million US dollars for a total production of 3300 MT head-on gutted salmon (Table 3).

2.3.3. Capital cost—LBCC-RAS model

The capital cost of the LBCC-RAS model farm includes all RAS systems, water supply, effluent treatment systems, buildings, engineering services, construction management services, a primary processing facility and general contractor bonding requirements. These components are itemized based on material, equipment, labor and subcontractor services, upon which the costs are estimated. Ten percent contingency is applied to capture uncertainty associated with this level of cost estimation. We assume that the lifespan of materials and equipment is 10 years and the lifespan for buildings and tanks is 20 years. These lifespans are used for calculation of depreciation and replacement cost. The cost of bonding is included as insurance may be required by owners that builders must have for large projects and is typically passed back to the owner. There are currently no comparable license costs for a LBCC-RAS farm in the US. The total capital cost including contingency of the LBCC-RAS model farm is estimated to be 53.6 million US dollars for a total production of 3300 MT head-on gutted salmon (Table 3).

2.3.4. Operating cost—ONP model

The operating cost for the ONP model farm is estimated based on data collected by the Norwegian Directorate of Fisheries (2014) and also Marine Harvest ASA (2014), and are the average costs of the last five years, 2009–2013. Since there are uncertainties associated with these items and the overall cost has increased gradually in the last several years, we applied a 2% increase for the first five year’s estimates, and a 3% increase for the remaining year’s estimate to account for uncertainties for each cost item. In other words, it is assumed that each cost item will increase 2% for the first five years.

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1 1 US dollar = 7 Norwegian kroners.
Table 4
Operating expenses for a 3,300 MT HOG LBCC-RAS and ONP Atlantic salmon farm.

| Cost item         | ONS system Cost (US$) | ONS system Cost (NOK) | LBCC-RAS system Cost (US$) | LBCC-RAS system Cost (NOK) |
|-------------------|------------------------|-----------------------|-----------------------------|-----------------------------|
| Feed              | 2.05                   | 14.34                 | 1.90                        | 13.33                       |
| Smolt             | 0.47                   | 3.30                  | 0.12                        | 0.86                        |
| Egg               | 0.31                   | 2.15                  | 0.52                        | 3.65                        |
| Labor             | 0.18                   | 1.23                  | 0.09                        | 0.62                        |
| Well boat         | 0.03                   | 0.18                  | 0.18                        | 1.27                        |
| Health            | 0.02                   | 0.16                  | 0.33                        | 2.32                        |
| Electricity       | –                      | –                     | 0.12                        | 0.83                        |
| Oxygen            | –                      | –                     | 0.15                        | 1.07                        |
| Water treatment   | –                      | –                     | 0.09                        | 0.62                        |
| Insurance         | 0.09                   | 0.60                  | 0.18                        | 1.27                        |
| Primary processing| 0.25                   | 1.58                  | –                           | 0.12                        |
| Transportation    | 0.09                   | 0.60                  | 0.47                        | 3.26                        |
| Sales & marketing | 0.14                   | 0.99                  | 0.65                        | 4.52                        |
| Maintenance       | 0.60                   | 4.21                  | 0.58                        | 4.09                        |
| Interest          | 0.18                   | 1.28                  | 0.49                        | 3.45                        |
| Depreciations     | 0.33                   | 2.32                  | 5.40                        | 39.27                       |
| Total             | 5.08                   | 35.37                 | 5.60                        | 39.27                       |

and 3% for the rest. The operating costs are the average estimates over 15 years. The breakdown of costs is presented in Table 4.

2.3.5. Operating cost—LBCC-RAS model

The operating cost for the LBCC-RAS model farm is estimated based on the biplan designed for an annual production of 3300 MT after primary processing. Cost items include feed, oxygen, bicarbonate, electricity, eggs, labor, stock insurance, interest and depreciation. Feed amount and thus cost, is calculated based on the feed required for growth multiplied by feed conversion ratio at different life stages. The amounts, and thus costs, of oxygen and bicarbonate are dependent on the feed required. Oxygen required is estimated to be 0.60 kg oxygen per kg feed, which includes an oxygen transfer efficiency of 75%. Bicarbonate required is estimated to be 0.20 kg bicarbonate per kg feed, which includes a base chemical availability of 75%. The cost of the electricity is determined by the RAS design, which identified all pumps and motors required for operation. The number, and thus cost, of eggs required is estimated by the assumed mortality rates at different life stages. Labor costs for the LBCC-RAS model farm include management (biological and maintenance), fish culture technicians, laboratory technicians, maintenance mechanics, and primary processing staff. It is assumed that insurance cost for the first year of operation is 4% of standing biomass, and then that declines to 2% of standing biomass in the following years. The ratio between interest and cash for capital cost and first year operating cost was 60/40, and an interest rate of 6% was used. Depreciation of each item was estimated using a straight line approach, meaning depreciation cost was charged evenly throughout the useful life of each capital item. Maintenance cost was estimated to be 10% of the total variable cost. To capture unknown costs, a contingency cost is also included which was assumed to be 10% of the total cost. The increase with 2% for the first 5 years and 3% for the rest are also applied for each cost item due to unforeseen future changes, same as the ONS system.

2.3.6. Sales and income

It takes approximately one year for salmon to grow to market size, therefore, there is no harvest for Year 1 and a proportionally smaller harvest for Year 2. In Year 3 and onwards, a constant harvest of 3300 MT is assumed for the ONP and LBCC-RAS systems. The price used here is the export market price of fresh gutted salmon in the US market, which is approximately 5.97 US$/kg or 41.8 NOK/kg averaged weekly price for the year 2014 (Statistics Norway, 2015). It is also assumed that the price for salmon in the future would increase in a similar way as the cost items, i.e., increased by 2% for the first five years and 3% for the rest. However, preliminary sales of Atlantic salmon produced by a LBCC-RAS farm have commanded a significant price premium (Guy Dean, Albion Fisheries (Vancouver, BC), personal communication, September 4, 2014), hence a 30% price premium is assumed which is approximately 7.76 US$/kg. The total sales revenue is calculated based on export price and annual harvest.

2.4. Carbon footprint

The carbon footprint is the sum of potential climate impacts that a product causes from a defined part of its life cycle. The carbon footprint was calculated using life cycle assessment (LCA) methodology that is a tool for environmental assessment (ISO, 2006a,b). It assesses the inputs of energy and material to the system and from that calculates potential environmental impacts caused by the resource use and outputs to nature in the form of emissions, waste and products. This LCA includes both direct emissions from the feed and salmon production and indirect emissions caused by production and distribution of the commodities and infrastructure that underpin the salmon life cycle.

The potential climate impact, the global warming potential, is calculated by characterizing all emission and impacts into CO₂ equivalents (CO₂eq) according to their radiative properties based on IPCC guidelines (IPCC, 2007). The goal of the carbon footprint was to compare the potential climate impacts from different ways of providing a retailer in Seattle, WA (US) with Atlantic salmon:

1a) Salmon from a LBCC-RAS system in the US running on electricity generated from a source that uses a typical mix of coal, gas, nuclear, wind and hydropower. Salmon is assumed to be transported fresh to the retailer 250 km by truck.

1b) Salmon from a LBCC-RAS System in the US running on electricity generated from a source that uses 90% hydropower and 10% coal. Salmon is assumed to be transported fresh to the retailer 250 km by truck.

2a) Salmon from a Norwegian ONP system. Salmon is assumed to be transported fresh, first with truck in Norway to Oslo, 520 km, and then with airfreight to Seattle, 7328 km.

2b) Salmon from a Norwegian ONP system. Salmon is assumed to be transported frozen, first with truck in Norway to Oslo, 520 km, and then with ship from Ålesund, Norway, to Seattle through the Panama Canal, 16,473 km.
Table 5
Inventory data for carbon footprint for two production models (LBCC-RAS system and ONP system) for a 3300 MT HOG Atlantic salmon farm. All numbers are per ton of salmon produced or transported.

|                          | Unit | LBCC-RAS System | ONP system |
|--------------------------|------|-----------------|------------|
| Feed, economic FCR       | ton  | 1.09            | 1.27       |
| Concrete                 | kg   | 82.5            | –          |
| Steel, reinforcing       | kg   | 14.40           | 0.63       |
| Steel, chromium 18/8 steel | kg | –               | 0.70       |
| Glass fiber              | kg   | 8.93            | –          |
| Nylon                    | kg   | –               | 1.01       |
| Polypropylene            | kg   | –               | 1.79       |
| Polyethylene             | kg   | –               | 0.28       |
| Fuel                     | l    | 10.50           | –          |
| Electricity              | kWh  | 5460            | –          |
| Oxygen (liquid)          | kg   | 656             | –          |
| Lime (calcium carbonate) | kg   | 219             | –          |
| EPS for transport packaging | kg | 25              | 25         |
| Ice                      | kg   | 300             | 300        |

The functional unit for the assessment, the basis for comparison, was 1 kg of gutted salmon with head on, at the retailer gate. For each case, the assessment included the complete production system, from production of feed ingredients, smolt production and construction of facilities, equipment and transports.

It was assumed that the salmon was gutted close to the production facility and that all byproducts, such as guts, skin and trimmings were utilized mainly for feed production. Mass allocation was applied meaning that the carbon footprint up to slaughter was allocated between the head-on-and-gutted salmon and the byproducts based on their mass. Thus, per unit of mass live salmon and head on and gutted salmon have the same carbon footprint. Important cut-offs, processes that are not included in the assessment include: slaughtering process, treatment of the biosolids from the LBCC-RAS system, and transport infrastructure.

2.4.1. Carbon footprint data
Table 5 presents important activity data for the carbon footprint of the two systems. Data for the LBCC-RAS system was derived from the concept-level design. Data for the Norwegian ONP system is gathered from industry actors and industry statistics (Winther et al., 2009; Hognes et al., 2011, 2014). Data on the climate impacts from capital and operational inputs were modeled with data from the LCA inventory database Ecoinvent v3.1 (2013). Since many of the operations performed at the ONP farm are performed by sub-contractors, and the extent of the activities, e.g., cleaning and priming of nets, are dependent of exact location, these data are based on the assumption of a representative production model.

Both the LBCC-RAS and ONP systems are modeled using the same feed. Based on LCAs of the average Norwegian salmon feed in 2012, the feed is associated with a carbon footprint of 2.5 kg CO2eq/kg feed at the feed factory gate. This is a feed with the following composition: 12% marine oil; 19% marine protein; 19% oil from crops; 39% protein from crops; 8% starch from crops and 3% micro ingredients (minerals, vitamins, pigments and other). This carbon footprint reflects a feed where 50% of the soy in the feed is equal to the average Brazilian soy, as modeled by the Agrifootprint database (Centre for Design and Society of the RMIT University, 2014), and the remaining coming from old farms where climate impacts from land use change is not included (Hognes et al., 2014).

Electricity for the LBCC-RAS system in case 1b is modeled as being generated from 90% hydropower and 10% coal power with data from Ecoinvent v3.1 (2013). This case is included as an illustrative case for what is possible if this type of electricity is available. Electricity loss of 3.5% was included for the transmission of the power and transformation from high to medium voltage. This associated the electricity with a carbon footprint of 0.04 kg CO2eq/kWh. For comparison, the Ecoinvent v3.1 database also provides a dataset that describes the electricity available in the regional entity of the North American Electric Reliability Corporation (NERC), that gives a carbon footprint of 0.64 kg CO2eq/kWh. This was the electricity data used for the LBCC-RAS system in case 1a.

Road transport was modeled with a truck carrying 20 tons of fish, consuming 3.7 L of diesel per 10 km and has a carbon footprint of 0.09 kg CO2eq/ton; this also includes fuel used for the refrigeration system and emission of refrigerants (Winther et al., 2009). The fuel consumption reflects a modern truck. For the ONP system in case 2a, airfreight was modeled using data for a Boeing 747–400 from the Agrifootprint database, with an emission factor of 1.18 kg CO2eq/tkm (Centre for Design and Society of the RMIT University, 2014). This plane is assumed to use 100% of its load capacity (3600 tons) and the emissions include landing and takeoff for a flight of approximately 10,000 km. For the ONP system in case 2b, ship transport was modeled with data for a ship of 120,000 tons (dry weight) utilizing 80% of its capacity, with an emission factor of 0.004 kg CO2eq/tkm. Emissions from preparing for the return of the ship and re-loading is included in this data. Fuel for running refrigeration systems and emissions of refrigerants were also included with an emission factor of 0.1 kg CO2eq/h (Winther et al., 2009).

3. Results

3.1. Financial analysis

3.1.1. Capital cost
Tables 3 reports the capital cost of ONP and LBCC-RAS systems. In the ONP system, the largest cost is license fees, which are almost 80% of the total capital cost, while the physical structure cost only accounts for 20%. For LBCC-RAS, the largest cost is the ras system which is half of the total cost; 18% of the LBCC-RAS capital cost is for building structures. The capital cost of LBCC-RAS is 80% higher than that of the ONP system given the same production capacity. It is important to note that the replacement costs of some cost items are not included in this table, but incorporated into the cash flow analysis.

3.1.2. Operating cost

The operating cost breakdowns for the two systems are presented in Table 4 and Fig. 2. The total operating costs for the two systems are relatively similar, with LBCC-RAS only 10% higher than the ONP system. Without interest and depreciation, the two production systems have an almost equal operating cost, 43.30 US$/kg for ONP and 43.37 US$/kg for LBCC-RAS. Feed is the single biggest cost item accounting for 41% and 34% of the total operating cost for the ONP and the LBCC-RAS systems, respectively. It is worthwhile to note that these operating costs are subject to change with site selection due to differences in power costs, feed shipping costs and other factors. For example, operating costs presented here do not include the cost of heating or cooling that may or may not be required based on the geographic location of the LBCC-RAS facility.

3.1.3. Financial indicators

The financial analysis is conducted for a period of 15 years; the discount rate is set to seven percent. The summary of the financial analysis is presented in Table 6. Overall, the ONP model system is financially better than the LBCC-RAS model system, even when the LBCC-RAS is selling product with a price premium. All three cases generate positive operating margins, indicating that from a production operating perspective, all are financially viable. The LBCC-RAS system selling salmon at a price premium is comparatively as profitable as the ONP system, even though its NPV is negative (~20,340,000 US$) and its return on investment (9.01%) is lower than the ONP system’s ROI (17.77%). However, when selling
salmon at the same price as the ONP system, the LBCC-RAS system is barely financially profitable and not an attractive investment. To be comparable with an ONP system, the LBCC-RAS system must command higher market price to break even or be profitable.

The IRR can be considered as the true expected yield from an investment. The IRR before EBIT for the LBCC-RAS with price premium is calculated to be 13.28%. The real IRR for the LBCC-RAS with price premium is 2.67%. The discount rate of 7% used here is below the IRR before EBIT and thus the LBCC-RAS would be an investment that results in a positive NPV. However, the discount rate of 7% used here is also above real IRR, and that investment in LBCC-RAS results in a negative NPV. Investors must make investment decisions based on her expectation(s) on return, whether using the IRR of 13.28% or 2.67%.

### 3.1.4. Sensitivity analysis

The financial results are very sensitive to some factors. For instance, prices have substantial influence on the results, and are subject to short- and long-term fluctuations due to dynamics in supply and demand. Feed is the largest cost item, so any changes in feed price and feed utilization have large impacts on the economic performance of the operations. Recent figures have suggested the cost of feed has increased gradually. The assumption for feed conversion ratio during growout is one of the most critical values in the estimation because it drives the largest component of the cost of production—feed cost during growout. Performance data from repeated Freshwater Institute trials indicate a feed conversion ratio less than 1.1 during the final growout phase (Summerfelt et al., 2013); utilizing lower FCR values during final growout instead of 1.1 would reduce the cost of production, by potentially up to 6%. Feed is also the major factor influencing the carbon footprint. Other factors such as mortality rates, power cost and mortality also have impacts on financial performance.

### 3.2. Carbon footprint results

If the alternative is intercontinental export of fresh salmon by air, then a modern and efficient LBCC-RAS system close to the market can be a more climate friendly alternative, even when running on electric power that mainly originates from fossil fuels (7.4 versus 15.2 kg CO$_2$eq per kg HOG salmon at retailer gate in Seattle). If the LBCC-RAS system is running on 90% hydropower the carbon footprint of the LBCC-RAS salmon is further reduced to 4.1 kg CO$_2$eq per kg HOG salmon at the retailer gate. The most climate friendly alternative of all is to ship frozen salmon from Norway with a modern container ship, 3.8 kg CO$_2$eq per kg HOG salmon at the retailer gate. A frozen product is not directly comparable with a fresh, but with modern freezing technologies, the quality of frozen products is not necessarily inferior to fresh.

At the producer gate, before transport to the retailer in Seattle, the production systems have climate impacts per unit produced of 3.4 versus 3.7 and 7.0 kg CO$_2$eq/kg salmon live-weight for the ONP and the LBCC-RAS using hydropower or average fossil fuel based electricity, respectively (Table 7 and Fig. 3).

The more general findings confirmed what previous LCAs have found that fish feed is the dominant climate aspect for the selected salmon products, but that energy used in growout and emissions from transports are also important. Production and maintenance of equipment and production facilities are not important climate aspects compared to feed production, transport and water treatment.

### 4. Discussion

Given current technology development and possible increases in market price for salmon and production input factors, the ONP system still remains the most profitable, even at this relatively small scale. To achieve comparative financial performance, the LBCC-RAS system requires a price premium, at least 25% higher than current market prices. This is mainly due to considerably
higher capital cost for the LBCC-RAS system. However, the difference in operating costs between both systems is relatively small. If the feed conversion ratio can be further improved from 1.1 to 1.0 for LBCC-RAS systems, the gap will be even smaller since feed is the most important cost item. However, improvements in feed conversion ratio are also likely to happen in ONP systems, so the difference in the future for optimized systems is hard to predict.

It is important to note that ONP systems are just for the growout phase in Norway, and that salmon now spend more of their lifecycle in LBCC-RAS smolt production facilities (Dalsgaard et al., 2013). Additionally, other costs such as managing sea lice and loss due to disease could further increase the operating cost of ONP systems significantly (Liu and Bjelland, 2014). The largest limiting factor for using LBCC-RAS system appears to be the capital cost. Thus, there are economic incentives for advancing technological innovations of LBCC-RAS systems that can reduce capital cost to become more competitive with ONP systems.

LBCC-RAS systems are not a new technology, and have been used for the last twenty years for growing out both freshwater species, such as eel and catfish, and marine species like trout and sea bass (Martins et al., 2010; Badiola et al., 2012). There is increasing interest in applying LBCC-RAS for the salmon smolt stage in Nordic countries and Europe (Dalsgaard et al., 2013). However, due to low returns on investment and and a history of failures when the technology was not well advanced, LBCC-RAS have not been used widely.

Economic incentives have been proven to be more effective than traditional command and control policy (Bailly and Willmann, 2001; Liu et al., 2013). Market-based economic instruments such as taxes, subsidies, fees/charges and eco-labeling can create incentives for the industry to foster cost-effective technology innovation and adaptation such as LBCC-RAS systems or other closed containment systems (Rosten et al., 2013). However, such incentive-based approaches have to be executed with the vectors of market and social forces such as environmental policy and consumers. Eco-

Table 7

|                        | 1a) Feed production | 1b) Construction of facility and equipment | 2a) Grow out and smolt (fuel and electricity) | 2b) Oxygen and lime | 3a) At producer gate (live weight) | 3b) Transport, road | 4a) Transport, air or water | 5a) Packaging and ice | 6a) Refrigeration during transport | 7a) At retailer gate (HOG) |
|------------------------|---------------------|-------------------------------------------|---------------------------------------------|--------------------|-----------------------------------|----------------------|--------------------------|----------------------|-----------------------------|--------------------------|
| Feed production        | 2.69                | 2.69                                      | 3.21                                        | 3.21               | 4.14                              | 0.00                 | 0.00                     | 0.37                 | 0.00                        | 7.41                     |
| Construction of facility and equipment | 0.39             | 0.39                                      | 0.02                                        | 0.02               | 0.44                              | 0.03                 | 0.06                     | 0.37                 | 0.00                        | 4.14                     |
| Grow out and smolt (fuel and electricity) | 3.48             | 0.21                                      | 0.16                                        | 0.16               | 3.73                              | 0.03                 | –                        | 0.37                 | 0.00                        | 4.14                     |
| Oxygen and lime        | 0.44                | 0.44                                      | –                                           | –                  | 3.39                              | –                   | 0.09                     | 0.37                 | 0.11                        | –                        |
| At producer gate (live weight) | 7.01              | 3.73                                      | 3.39                                        | 3.39               | 0.21                              | 11.40                | 0.09                     | 0.37                 | 0.11                        | –                        |
| Transport, road        | 0.03                | 0.03                                      | 0.06                                        | 0.06               | –                                 | –                   | 0.09                     | 0.37                 | 0.11                        | –                        |
| Transport, air or water| –                   | –                                         | –                                           | –                  | –                                 | –                   | 0.09                     | –                   | –                           | –                        |
| Packaging and ice      | 0.37                | 0.37                                      | 0.37                                        | 0.37               | –                                 | –                   | –                        | –                   | –                           | –                        |
| Refrigeration during transport | 0.00           | 0.00                                      | 0.00                                        | 0.00               | –                                 | –                   | –                        | –                   | –                           | –                        |
| At retailer gate (HOG) | 7.41                | 4.14                                      | 15.22                                       | 3.75               | –                                 | –                   | –                        | –                   | –                           | –                        |

Fig. 3. Estimated carbon footprint with component contributions at the producer gate and the retailer gate for the following scenarios: (1a) Salmon from a LBCC-RAS system in the US running on a typical electricity mix; (1b) Salmon from a LBCC-RAS system in the US running on electricity generated predominantly from hydropower; (2a) Salmon from a Norwegian ONP system transported by airfreight to Seattle; (2b) Salmon from a Norwegian ONP system transported by ship to Seattle.
labeling farmed products would be a market-driving power to change consumers’ purchasing behavior. Concerned consumers are likely willing to pay more for the products which are produced in an environmental sustainable way. Subsidies and taxes can be used to stimulate cost-effective technology innovation and adaptation, e.g., rewarding improved environmental performance from capturing and controlling waste streams in closed-containment systems or eliminating sea lice infestation. While environmental policies may also have a role, in Norway, “green” concessions for salmon farming require the aquaculture industry to employ technological and operational innovations and solutions to reduce the incidence of salmon lice and escapes. These technologies require upfront investment which can be significant, but over the long run, such technological innovation would increase social license to operate through improved environmental performance and reduced conflict with other resource users, perceived market payoffs through reduced costs to obtain and maintain a license to operate, and monitor and mitigate negative impacts, e.g., costs of recapturing escapes. Captured nutrient laden waste streams associated with LBCC-RAS may also result in ancillary revenue streams, e.g., aquaponics.

The carbon footprint analysis showed that, with respect to climate impact, producing close to the market is preferable by a good margin, especially when the LCBC-RAS system utilized electricity generated from 90% hydropower and the alternative is to export fish fresh, fast and a long distance. Even if salmon is LCBC-RAS produced with electricity based on fossil fuels, intercontinental export of fresh fish on airplanes is not a preferable option. However, environmental considerations involving high inputs of electricity should be followed up with a discussion of what is the environmentally optimum way of using available electricity. Electricity is of the highest energy quality available, and many industrial and infrastructure processes do not have an alternative to electricity. Export of frozen salmon was the best option of all, but cannot be directly compared with fresh salmon. Still, this result points to a future option, with product development, improvement of logistic chain management, to maintain quality through the transport, and market acceptance, frozen intercontinental export has the potential to compete with local LCBC-RAS products. Another important assumption regarding transport is that most intercontinental export of fresh Norwegian salmon is done with flights that also carry passengers. Thus a more precise comparison should include details and insight into how it is reasonable to allocate the fuel used and corresponding emissions between goods and passengers. In addition to this, the LCA data that is available on flight transport is highly variable. This indicates that more precision on the exact age/technology and size of the aircrafts being used should be included.

The carbon footprint contained several cut-offs and assumptions that limits the conclusions that can be drawn, e.g., the same data on feed was used for salmon production in the US and Norway. There are likely to be differences in the carbon footprint of the feeds that would actually be used. A potentially important cut off is that treatment of the biosolids was not included. Biosolids could be seen as both waste and a resource, but either way handling it will involve the use of both energy and transports together with emissions from the biosolids itself. Still, this aspect was left out because it would be difficult to compare to the ONP system, where there is no biosolids capture and waste feed and feces is discharged directly in the ocean.

Most often, the concentrated effluent of LBCC-RAS systems now in operation in North America and Europe are treated in order to meet stringent wastewater discharge permits. Thus a flow-through system will have a higher eutrophication potential. However, if the concentrated effluent of a LBCC-RAS is not treated there is no such advantage to be obtained. Rosten et al. (2013) suggests a classification system for closed containment systems from 1 to 4, where category 4 is the most closed system towards the external envi-

| System and method | Feed efficiency | Carbon footprint of the product (kg CO₂-eq/kg) | Reference |
|-------------------|----------------|-----------------------------------------------|-----------|
| Net-pen: 1.49     |                |                                              | Ayer and Tyedmers (2009) |
| Land, flow-through, bag: 1.17 |                |                                              |           |
| Land, land-rearing: 1.46 |                |                                              |           |
| Intensive flow-through, bag: 2.36 |                |                                              |           |
| Intensive flow-through, bag: 2.25 |                |                                              |           |
| Land, flow-through, bag: 2.36 |                |                                              |           |
| Recirculating, bag: 1.46 |                |                                              |           |
| Recirculating, bag: 1.47 |                |                                              |           |
| Semi-closed, bag: 6.38 |                |                                              |           |
| Semi-closed, bag: 6.10 |                |                                              |           |
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environment applying treatment of both inlet and outlet of a LBCC-RAS system. Acidification and toxic potentials are strongly connected to energy consumption and thus similar to climate impacts with regards to where and why they occur.

Aquaculture technologies have been compared with LCA previously; our assessment was compared with a selection of peer reviewed literature (Table 8). This selection of literature points to the same main conclusions: feed production is a dominating factor for carbon footprint in salmon aquaculture, and for LBCC-RAS, the use of energy for water treatment can be equally important and equipment and infrastructure is of minor importance. The importance of energy used for water treatment depends on how this energy is produced. The literature also shows that important parameters for the LCA, such as the FCR and energy used for water treatment varies considerably. This study has not gone into the details to explain these differences, but important reasons are probably that the studies rely on different assumptions, experimental data and site specific properties. These differences make it difficult to compare the final carbon footprint among studies. In addition to differences in the aquaculture systems that are compared, it is also not possible to be sure that the data on feed that are used are comparable. Finally, there are also methodical differences, e.g., Ayer and Tyedmers (2009) used allocation based on the energy content in the different outputs rather than their mass and Samuel-Fitwi et al. (2013) used system expansion.

The conclusion with regards to the hypothesis that a LBCC-RAS produced salmon will have a higher carbon footprint than one from an ONP system is solely dependent on what carbon dioxide emission the electricity production is attributed with and the method and form that the product is transported to market with. If the electricity for the LBCC-RAS is considered to be primarily hydropower then the carbon footprint for the two systems at the producer gate are relatively close (3.39 and 3.73 kg CO2eq/kg salmon live-weight). If the electricity for the LBCC-RAS is considered to be the average US mix dominated by fossil fuels, then the LBCC-RAS has a higher carbon footprint at the producer gate (7.01 versus 3.39 kg CO2eq/kg salmon live-weight). The carbon footprint demonstrates the importance of the emissions associated with electricity generation for LBCC-RAS systems.

In a market where electric power is a commodity in short supply, and where power markets are connected through economy and/or the grid, it is challenging to argue that power is supplied from one specific source. On top of this, renewable energy, such as hydropower, is often sold to clients that pay extra for a certificate to claim that their electricity is produced from renewable sources. For this system to work, as well as for carbon footprint, it would require a mechanism that ensures that the sum of certificates that are sold do not exceed the renewable power that is actually available and that everybody who does not buy certificates uses a carbon footprint of their electricity that does not include the renewables that are sold with certificates. This is what is then called the residue mix. As far as these authors know, no such system exists today and it is recognized to be “good practice” to use the average production mix in the grid where the electricity use takes place. The grid here being what is physically and/or economically connected.

Extending the carbon footprint to include transport to market for the most likely production systems, fresh salmon produced in LBCC-RAS systems close to a US market that use an average US electricity mix and fresh salmon produced in Norway in ONP systems shipped to the same market by airfreight, yields the result that LBCC-RAS has a much smaller carbon footprint, 7.41 versus 15.22 CO2eq/kg salmon HOG, respectively. In this case the carbon footprint associated with transport is the dominant factor for ONP produced salmon, accounting for more carbon footprint than the entire production on a kg salmon HOG basis (Fig. 3).

5. Conclusions

In this paper, we compare the economic and environmental performance of the Norwegian open net pen system in the sea and the US land-based, closed containment water recirculating aquaculture system for the same production capacity targeting the same US market. The scale used for the open net pen system is smaller than the average operation scale in Norway, so both systems could be scaled up to higher production capacity. This will result in reduction in cost due to scale of economy. However, the main findings are drawn:

- Capital cost for land-based closed containment water recirculating salmon farming systems is significantly greater than capital cost for traditional open net pen salmon farming systems, but increasing net pen site license costs in Norway are bringing the capital costs closer.
- Production cost for land-based closed containment water recirculating salmon farming systems is approximately the same as production cost for traditional open net pen salmon farming systems at this scale, when excluding interest and depreciation.
- Return on investment for traditional open net pen salmon farming at this scale is twice that of land-based closed containment water recirculating salmon farming, when land-based produced salmon are sold at a price premium.
- Internal rate of return for earnings before interest and tax for traditional open net pen salmon farming at this scale is only slightly greater than that of land-based closed containment water recirculating salmon farming, when land-based produced salmon are sold at a price premium.
- The carbon footprint of salmon produced in land-based closed containment water recirculating aquaculture systems that are using a typical US electricity mix based on fossil fuels is twice that of salmon produced in traditional open net pen systems, when delivery to the market is not included.
- The carbon footprint of salmon produced in land-based closed containment water recirculating aquaculture systems delivered to market in the US is less than half of that for salmon produced in traditional open net pen systems in Norway that is delivered to the US by air freight.

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