Energy use in Recirculating Aquaculture Systems (RAS): A review

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Highlights

- RAS energy use is a drawback, increasing operational costs and environmental impact
- RAS design should comprehend water and energy use, waste discharge and productivity
- Economic and environmental sustainable RAS is achieved quantifying all energy flows
- Fossil based fuels are less cost-effective and renewable energies of potential use

Abstract

Recirculating aquaculture systems (RASs) are intensive fish production systems, with reduced use of water and land. However, their high energy requirement is a drawback, which increases both operational costs and the potential impacts created by the use of fossil fuels. Energy use in RAS has been studied indirectly and/or mentioned in several publications. Nevertheless, its importance and impacts have not been studied. In aiming to achieve economic and environmentally sustainable production a compromise has to be found between water use, waste discharge, energy consumption and productivity.
The current review discusses published studies about energy use and RAS designs efficiencies. Moreover, with the aim of making an industry baseline study a survey about the energy use in commercial scale RAS was conducted. The design of more efficient and less energy dependent RAS is presented, including optimized unit processes, system integration and equipment selection. The main conclusions are: fossil based fuels are less cost-effective than renewable energies; energy is of little concern for the majority of the industry, and renewable energies are of potential use in RAS.

**Keywords:** energy use, Recirculating Aquaculture Systems, environment, optimized-designs, cost-effectiveness, sustainability

1. Introduction

Animal farming, including fish farming, may cause significant environmental problems such as resource depletion as well as contributing to climate change (Winther et al. 2009; Sonesson et al. 2010; Lesschen et al. 2011; Nijdam et al. 2012). Intensification of farming practices (Steinfeld and Wassenaar 2007) together with the steady increase in the demand for fish (FAO 2014) has pushed the aquaculture industry to look for acceptable practices from environmental, societal and economic perspectives. In aquaculture, water and energy are two of the main resources to be considered (d’Orbcastel et al. 2009 a). They are indeed the baseline for industry development (COM 2002; COM 2009; NOAA 2011). Consequently, an improvement in water management will aid aquaculture’s progress (Dumont et al. 2012), which has slowed down recently for some forms of fish farming (e.g. flow-through systems) (Naylor et al. 2000; Buschmann et al. 2006).
Compared to other forms of aquaculture production, recirculating aquaculture systems (RASs) decrease potential environmental impacts such as eutrophication as well as water dependence (Verdegem et al. 2006; d’Orbcastel et al. 2009 b; Eding et al. 2009), aiding waste management (i.e. reduced waste volumes) and boosting nutrient recycling (Piedrahita 2003). RAS are intensive fish production systems, with reduced water and land use. Nevertheless, their high energy requirement is a challenge which increases operational costs (Aubin et al. 2006; Colt et al. 2008; d’Orbcastel et al. 2009 a,b). Thus, on-farm electricity consumption affects both environmental impacts and economic costs (i.e. operational costs) of a RAS (Badiola et al. 2017), jeopardizing the farms’ sustainability. Currently, there is interest in using renewable energy sources or waste heat from other industries as part of the solution to decrease environmental impacts due to the use of fossil fuels. Nevertheless, the energy source to be employed in a farm will be dictated by the system’s location and accessibility to the energy sources. The location of aquaculture operations, sometimes in remote areas, may make it easier to use renewable energy than in other industries.

In 2013, the food sector was a major consumer of energy, accounting for 26% of the European Union’s final energy consumption (Monforti-Ferrario et al. 2015). Agriculture and livestock production were responsible for 33.4 % of the energy costs associated with food consumed in the EU, this represents the largest contributing sector. Moreover, the energy consumed in the fishery sector including aquaculture was equivalent to almost 5 % (i.e. 45 Petajoule) of the direct energy consumed in the agriculture sector. Clearly, energy plays a vital role in food production around the world (Dincer 1999; Midilli et al. 2005a; 2005b).
A possible solution to decrease energy usage and increase production efficiencies may be creating energy efficient production systems. This is recognized as a cost-effective way of addressing the wide-ranging problems associated with: the changing global energy scene (i.e. reducing dependence on fossil fuels while increasing the use of renewable sources); mitigation of greenhouse gas emissions from industry (Worrell et al. 2009); and industry’s economic competitiveness promoting cost savings (Worrell et al. 2003). In fact, tracking sector-wide energy efficiency trends has grown in importance (Ang et al. 2010) due to its direct relationship with the improvement of industrial process productivity (i.e. lower capital and operating costs, increased yields, and reductions in resource and energy use) (Kelly et al. 1989; Boyd and Pang 2000).

In RAS, as in other forms of aquaculture, operating costs should dictate the most efficient design. Little has been published about the energy use and energy efficiency in RAS. The few examples include the work done by Colt et al. 2008; d’Orbcastel et al. 2009 a,b; Buck 2012; Ioakeimidis et al. 2013.

The main objective of this paper is to provide an in-depth analysis of the energy demand of RAS aquaculture. Current trends in energy use, energy sources and energy efficiency in the sector are analyzed based on an extensive literature review (including over 200 publications and 58 books) and a survey of stakeholders’ points of view regarding energy-related challenges. Finally, results are used to propose optimized RAS unit processes, engineered system integration, and equipment selections as guidance for designing RAS farms. Alternative design solutions for each system, subsystem, and component are presented as well.
2. Current RAS industry worldwide

The number of RAS farms around the world is steadily increasing (Martins et al. 2010; Badiola et al. 2012, 2014; Dalsgaard et al. 2013). This is reflected in the latest publications and in some worldwide survey made by the authors through personal communication and social networking. Data compiled in the research is reflected in Figure 1 (i.e. worldwide countries ranged according to the number of RAS companies) and Table 1 (i.e. Europe’s fish production in RAS between 1986 and 2014). In the US and Europe, the number of RAS installations is around 360 (USDA 2013 Census of Agriculture; Badiola et al 2014). Norway and Canada represent important RAS industry countries, mainly for salmon production (Dalsgaard et al 2013), while China is increasing its yearly production with the construction of new, large indoor RAS facilities (Murray et al 2014). Salmon, tilapia, trout, eel, turbot, catfish and shrimp represent the main species farmed (Badiola et al 2012). This increased number of RAS farms around the word inherently implies the use of energy and its consequences both for companies (i.e. economic) and the environment (i.e. regional and global).

*FIGURE 1*

*TABLE 1*
Table 1. Europe’s fish production in RAS between 1986 and 2014: grow-out (normal); smolt (bold); fingerlings (italics). Data updated from Sturrock et al. 2008, Bergheim et al. 2009, Martins et al. 2010, and Murray et al. 2014

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* with partial recirculation only
3. Energy use in RAS:

Energy use and its associated cost and environmental impact depend on the source and quantity of energy used, location, design and management. The following section discusses the implication of design on efficiency and energy use. It also provides an overview on the most frequent equipment and processes used in RAS, different energy sources, and energy consumption values for production of different species.

3.1. Temperature control and disinfection units

In RAS water is re-used after undergoing different treatments (i.e. water treatment loop); the remainder, after being treated, is discharged into an appropriate water body (e.g. the sea, a lake, a river). Hence, an equal amount of clean water from an external water body (e.g. the sea, a river, a municipal water source) is pumped into the RAS system to maintain a constant volume of water (Rosenthal et al. 1986). The water treatment loop is formed by different unit operations. Some require energy (e.g. pumps); others (e.g. biofilter) influence the energy consumption due to their design and/or management (e.g. equipment height determines pumping head and energy needed), despite not needing energy directly to power the equipment. Each RAS is different and the technology to be used in the water treatment loop may differ between systems. Thus, the operations requiring energy use in RAS and the overall energy requirement will be determined by engineering and operational criteria, such as: water circulation, including pumping of the incoming water and of water through the treatment loop; heating/cooling of water; oxygenation; filtration and/or removal of solids and nitrogen +

Water circulation
In RAS, water is usually circulated by pumps to move water to a higher elevation or to increase the overall system pressure for filtration, aeration and degassing. Depending on a system’s hydraulics, there are two RAS types: pressurized or high-head systems and low-head systems. The advantage of a pressurized or high-head RAS is the hydraulic link between source and the point of discharge, which is relatively independent of the pipe’s geometry. However, a change in flow at one distribution point will influence flow at another point. In such systems centrifugal pumps are used. The efficiency of such pumps depends on the impeller’s design (e.g. open, enclosed, single or double suction, vane configuration) which can limit the size of solids that pass through the pump. In contrast, low-head RAS present the advantage of moving large volumes of water using significantly lower energy, improving the economic returns of investment (Pfeiffer and Wills 2008; Pfeiffer and Riche 2011). In such systems, either airlift pumps, axial-flow propeller pumps or some combination of the two is used.

Due to limited head capacity, airlift pumps have has been generally thought to be insufficient to provide the water treatment requirements of high-density large capacity RAS, while axial flow pumps may be efficient at moving large volumes of water to modest head levels (e.g. 4.6 to 9.2 m) and tolerable to small debris and solids (Timmons and Ebeling 2010). The main disadvantage with airlift pumps is the low water delivery height, which is limited to a maximum of around 0.3 m. In those cases, the energy needed could be reduced by 40% compared to centrifugal pumps (Barrut et al. 2012). The head loss in most RAS is a limiting factor; operating costs can increase 20-40% at 1 m pumping head and over 44-69% at 3 m head comparing to traditional flow-through systems (Muir 1978).
Recently, due to the high operational costs of pumping (Dunning et al. 1998; Colt et al. 2008), airlifts are becoming more common (Blancheton et al. 2007; Mamane et al. 2010); they are simple to use and economic under a limited set of operating conditions. Moreover, this equipment can serve for water transport, gas exchange and foam fractionation (Barrut et al. 2012), which may have some advantages when compared to other pumping methods, such as a lower occurrence of breakdowns, a reduction of the need for technical supervision, and a reduced use of space (d’Orbcastel et al. 2009; Barrut et al. 2011). Energy costs of airlift pumps when used for low head water transport and aeration have been up to 35% lower when compared to standard pump and standard aeration combination (Reinemann et al. 1990; Kassab et al. 2009; d’Orbcastel et al. 2009 b).

*Oxygenation and aeration*

The availability of dissolved oxygen is usually the first factor that limits carrying capacity in RAS; hence the use of oxygenation enables adequate growing conditions, good biofilter performance, and a higher fish biomass in the system. Some systems rely on pure oxygen as the oxygen source while others use aeration to achieve both oxygen addition and carbon dioxide stripping.

The use of pure oxygen can reduce fish production costs by supporting higher fish and feed loading rates at reduced water flow requirements. In turn, it reduces: pump size and cost of pumping; culture tank size or number; size of water reuse equipment; and overall system size. Consequently, the configuration of a RAS determines, to a large extent, the
most appropriate type of oxygenation unit for a particular RAS as well as the placement of both the oxygenation and the aeration/stripping units (Summerfelt et al. 2000).

Fish respiration produces carbon dioxide, which is excreted across the gill as CO₂ gas (Colt et al. 2009), while a biofilter also consumes oxygen and generates carbon dioxide (Timmons and Ebeling, 2010). At undesirable concentrations, carbon dioxide may affect fish welfare and reduce water pH. The use of pure oxygen at relatively low specific water exchange rates, requires aeration for CO₂ stripping, the use of chemicals to adjust the pH of production tanks (i.e. adding alkalinity) or a combination of both (Bisogni and Timmons 1994; Grace and Piedrahita 1994; Loyless and Malone 1997).

Pure oxygen gas has been used since the 1970s in order to increase the productivity (i.e. intensifying fish production) and the cost-effectiveness of a RAS (Speece 1981). Nevertheless, providing oxygen to cultured fish may be costly when compared to the cost of feed (Seginer and Mozes 2012), and may be cost-effective only in large scale systems (Sowerbutts and Forster 1980). So the efficiency of oxygenation is important for both technical and economic reasons. Theoretically, in standard temperature and pressure conditions, i.e. 20ºC and 760 mm Hg respectively, oxygenation using pure oxygen as the gas phase could give up to five times the oxygen transfer rate of conventional aeration. In practice, respiration efficiencies for fish were recorded higher with pure oxygen (Mitchell and Kirby 1976). Oxygen transfer has been shown four times higher than with aeration (Petit 1980). Operational principles, techniques and equipment for oxygenation have already been well-established (Colt and Watten 1988; Watten 1994) and directions to choose the right oxygenation technology depending on each RAS layout have also been published (Summerfelt et al. 2000).
The choice of selecting one oxygenation system or another will ultimately depend on the economic and technical characteristics of each RAS (Seginer and Mozes 2012). When oxygen is supplied by the means of aeration there are various options and efficiencies of design, where surface aerators and packed column aerators are more efficient than diffused aeration systems and sub-surface aerators (Hackney and Colt 1982; Loyless and Malone 1998). When aeration is chosen for economic reasons to reduce equipment costs and usage, the optimal level of dissolved oxygen in the water (i.e. g of O₂/m³ water) is the lowest permissible where fish health is not impacted (Seginer and Mozes 2012), this level will depend upon the fish species and water temperature (Cerezo and Garcia 2004; Cerezo-Valverde et al. 2006).

Rosati et al. 1994 compared 3 types of oxygenation and aeration applications in RAS from the technical and economic perspective: (I) liquid oxygen used with a high efficiency dissolution device such as an oxygen column or a U-tube (total energy consumption while generating: 7.69 kWh/kg fish); (II) a surface agitator aerator (28.2 kWh/kg fish); and, (III) an air blower with air-stones (65.5 kWh/kg fish). Aeration with a paddlewheel aerator (i.e. no pure oxygen supply) is, according to above mentioned authors, the most economical for small indoor systems. However, the appropriateness of this method of aeration should be reviewed carefully in any case. For example, d’Orbacastel et al. (2009 a,b) reported that aeration energy accounted for around 20% of the total energy consumption in the production cycle of a small scale RAS.

Additionally, when capital costs and intensity of production are considered the ranking of these alternate systems may change. The production of liquid oxygen (including the
amount of energy needed to produce a unit weight of oxygen and the energy required to transport oxygen to the facility) for a large-scale RAS with temperature control accounts for 0.12% of the total energy used (Colt et al. 2008).

Filtration and/or removal (solids and nitrogen compounds)

Mechanical filtration removes particulate matter, while biological filtration removes dissolved wastes. Typically, a considerable amount of sludge is produced in RAS and this sludge must be treated before it can be disposed of (Losordo and Timmons 1994; van Rijn 1996; Shnel et al. 2002; Suzuki et al. 2003; Timmons and Ebeling 2010). The solids, which are removed as sludge, are composed mainly of fish excretions and uneaten feed, where the volatile (organic) fraction ranges from 50 to 92% (Piedrahita 2003; Gebauer 2004; Gebauer and Eikebrokk 2006; Mirzoyan et al. 2008). Typically, fish sludge is characterized by its low total solid content (1.5–3%) compared to other animal production or industrial wastewater (Mirzoyan et al. 2008). Moreover, waste characteristics may vary widely, depending on the fish species, feed, management and differences in decay of organic matter within the tanks (Van Rijn 1996).

Solids removal is accomplished by sedimentation, mechanical filtration or centrifugation (Van Rijn 1996). Rotating micro-screens (i.e. drum filters), granular filters and gravity settling units are the most common methods used to remove the solids (Liltvedt and Hansen 1990; Bergheim et al. 1993; Franco-Nava et al. 2004). Nevertheless, up to 95 % by volume of the suspended solids may have a diameter smaller (<20 µm) than mesh size in common filters (30-60µm) and are called ‘fine solids’ (Chen et al. 1993) and their removal is accomplished by foam fractionation,
chemical oxidation (e.g. ozonation), or biological oxidation. Critical factors in the removal of fine solids are: filtration cycle, particle size, solids loading, and pressure head allowed (Wheaton 1977; Spotte 1979). The selection of filtration to minimize pressure loss is critical in reducing operating costs, though this may be offset against particle size removal and backwash frequency. Depending on the amounts of solids present, fine solids filters may be used intermittently or on a side-stream to reduce operating costs.

From an energy consumption perspective, mechanical filtration requires energy for backwashing, in addition to providing the pumping energy to overcome the head loss through the filter. Normal operating power requirements may be increased up to five times during a backwash cycle, e.g. from 10 to 50 kWh (Csavas and Varadi (1980). Nevertheless, the use of additional air scouring, as an adjunct to water backwash, may reduce the power requirement (Burrows and Combs 1968). As for centrifugal filtration, their efficiency for solid removal is considered poor (Mayo (1976), and highly energy intensive (Wheaton 1977); hence its use is not recommended for aquaculture.

Various options are available for nitrification or biofiltration. The choice of a given filter will depend on the strategy taken for the bacterial culture (i.e. suspended growth or fixed film), which also depends on the strategy used to provide oxygen (Malone and Pfeiffer 2006). Use of suspended growth started in the last two decades (Avnimelech 1999, 2007; McIntosh 2001 Avnimelech and Kochba 2009), while biological fixed film processes have been used since the early 1980’s (e.g. Brune and Gunther 1981; Kaiser and Wheaton 1983; Losordo 1991). Hybrid equipment, systems incorporating aspects of both fixed and suspended-media operation, can also be found.
Within the technologies mentioned, many configurations are used, i.e. moving beds, down-flow filters, rotating biological contactors, trickle, up-flow and fluidized bed filters. Different studies have been published referring to their efficiency in terms of nitrogen removal, specific surface areas and material used (e.g. Chen et al. 1993; Malone et al. 1993; Summerfelt and Cleasby 1996; Kamstra et al. 1998; Eding et al. 2006; Malone and Pfeiffer 2006) but few have mentioned their energy requirements (Sandu et al. 2002).

Table 2 presents a summary of the main advantages and disadvantages of the usual technology used in RAS. The comparison has only focused on their efficiency. Some examples from the literature on their energy requirements and costs are also presented.

*TABLE 2*
Table 2. Main advantages and disadvantages of some common technologies employed in a water treatment loop

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<td>Increased energy consumption</td>
<td></td>
<td>Mayo, 1976; Wheaton 1977</td>
</tr>
<tr>
<td>Airlift pumps</td>
<td>Inexpensive; Simple to use; Combine several functions; Reduce space used</td>
<td>Not sufficient in high-density RAS</td>
<td>Lower energy costs than centrifugal pumps</td>
<td>Blancheton et al. 2007; Mamane et al 2010; Barrut et al 2011,2012; d’Orbcastel et al 2009 a</td>
</tr>
<tr>
<td>Axial flow pumps</td>
<td>Large volumes at modest heads</td>
<td>Low water lift</td>
<td>Lower energy costs than centrifugal pumps</td>
<td>Timmons and Ebeling 2010; Barrut et al 2012</td>
</tr>
<tr>
<td><strong>Oxygenation and aeration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygenation</td>
<td>Additional safety; Maintenance of fully saturated conditions.</td>
<td>Cost-effective in large scale RAS; Distribution/maintenance requirements</td>
<td>Small fraction of the total energy used in large-scale RAS hatchery</td>
<td>Sowerbutts and Forster 1980; Colt et al 2008</td>
</tr>
<tr>
<td>Aeration</td>
<td>Simple to manage; Little maintenance required</td>
<td>Increased operational costs; Limited efficiency; May be difficult to measure</td>
<td>Significant fraction of the total energy consumption</td>
<td>d’Orbcastel et al 2009 a</td>
</tr>
<tr>
<td><strong>Solids filtration/removal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentation</td>
<td>Proves a suitable process for clarification of lower flow rates (e.g. sludge flow produced by a screen separator)</td>
<td>Insufficient residence time to particle settle out; scouring of settled particles off the bottom; short circuiting of influent water direct to the outflow. Not suitable for clarifying untreated main wastewater flow from a farm; Capacity limitations</td>
<td></td>
<td>Cripps and Kelly 1996; Summerfelt 1998; Cripps and Bergheim 2000</td>
</tr>
<tr>
<td>Static screens</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating microscreens</td>
<td>Suitable where blockage is likely; Potential to gently remove particles with minimal damage</td>
<td></td>
<td></td>
<td>Mäkinen et al. 1988; Wheaton 1977</td>
</tr>
<tr>
<td>Rotating screens</td>
<td>Backwashing sludge can be reused/applied to farmland</td>
<td>Substantial backwash sludge which requires further thickening/dewatering</td>
<td></td>
<td>Bergheim et al. 1998</td>
</tr>
<tr>
<td>Rotating disc screens</td>
<td></td>
<td>Limited capacity in comparison with disc screens</td>
<td></td>
<td>Cripps and Bergheim 2000</td>
</tr>
<tr>
<td><strong>Wastewater sludge thickening/removal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity thickening settlers</td>
<td>Concentrated biosolids are land applied, composted or hauled to a landfill</td>
<td></td>
<td>0.763 kWh/unit</td>
<td>Henderson and Bromage 1988; Bergheim et al. 1998; Chén et al. 1997; 2002; Brazil and Summerfelt 2006; Sindilariu et al. 2009; Sharrer et al. 2010</td>
</tr>
<tr>
<td>Inclined belt filters</td>
<td>Reduces TAN leaching as rapidly separates biosolids from wastewater</td>
<td>More mechanically complex than geotextile or bag or gravity thickening settlers</td>
<td>24.95 kWh/unit (includes: solids pump; clarified water pump; belt filter; mixing tank mixer; polymer and alum storage mixer; polymer and alum dosing pump)</td>
<td>Ebeling et al. 2006; Summerfelt and Vinci 2008; Sharrer et al 2010</td>
</tr>
<tr>
<td>Nitrogen removal</td>
<td>Geotextile bag filters</td>
<td>Dewatered biosolids suitable for land application, composting, incineration or landfill. Increased TAN leaching as solids are stored in anaerobic conditions</td>
<td>Require the application of a polymer to enhance floc formation</td>
<td>19.15 kWh/unit (includes: permeate pump; polymer and alum storage mixer; polymer and alum dosing pump)</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>Rotating biological contactor</td>
<td>Plug-flow pattern increases removal efficiency</td>
<td>High costs; low volumetric efficiency</td>
<td>Relatively low volumetric removal rates (i.e. large sized biofilters)</td>
<td>Models to predict energy costs but many are variables affecting the energy use</td>
</tr>
<tr>
<td>Trickling filters</td>
<td>CO2 removal by degassing</td>
<td>Water cooling in summertime; Simplicity of design, construction, operation and management.</td>
<td>Risk of clogging; Additional solids removal necessary (settleable solids to the extent possible)</td>
<td></td>
</tr>
<tr>
<td>Moving bed bioreactors (MBBR)</td>
<td>Low head loss; high specific biofilm surface area; no backwashing needed; low maintenance; small footprint</td>
<td>The efficiency is highly dependent on the media used and working parameters fluctuations (e.g. temperature)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downflow microbead filters</td>
<td>Smaller media, increased surface area</td>
<td>High hydraulic loadings possible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluidized sand biofilters</td>
<td>High specific surface area</td>
<td>No aeration</td>
<td>Narrow water flow range</td>
<td></td>
</tr>
<tr>
<td>Fluidized bed filter using plastic media</td>
<td>High specific surface area per unit volume (reduced hydraulic retention)</td>
<td>Reduce energy costs</td>
<td>High head loss, increasing energy requirements</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Available energy sources

The peak of the fossil fuel era has already passed and the use of renewable energy sources is expected to increase significantly (Monforti-Ferrario et al. 2015), up to 30–80% in 2100 (Fridleifsson 2001). In Europe, according to the Europe 2020 initiative, renewable energies should account for 20% of the energy produced by the year 2020 (COM 2016). Hydropower and traditional biomass are already important sources in the world’s energy mix, contributing about 18% of the total world energy requirements. Meanwhile, the new renewables (i.e. solar, wind and geothermal) contribute only about 2% of the present world primary energy use. In fact, solar energy for electricity production is still not commercially competitive in many places, while biomass, wind and geothermal energy are making relatively fast progress (Fridleifsson 2001).

In this context, in order to find solutions to problems such as the global warming potential, it will be necessary to integrate local energy sources into national/regional systems making use of the most appropriate local and imported energy (Fridleifsson 2001). Therefore, energy conservation at the farm scale (Rosen and Dincer 2001) and replacement of fossil fuels by renewable sources should be supported by industry stakeholders (Aubin et al. 2009).

In the aquaculture literature there are few contributions regarding: (I) the use of renewable energy sources; (II) advantages and/or disadvantages and comparisons between them; and, (III) operational costs related to each.
Geothermal energy

Geothermal energy can be used for both electricity and hot water generation for the processing of agricultural products and rearing fish in aquaculture, depending on the temperature and chemistry of the resources. Heat exchangers are often necessary when using geothermal energy due to chemicals in the geothermal waters, such as arsenic and dissolved gases, which are a major problem with regard to plants and animals. The use of geothermal energy in aquaculture is particularly attractive as the temperature range required varies between 25-35°C (i.e. warm water species) for which there is an abundance of geothermal resources (Lund 2013). The main advantages for RAS are the immediate use of the heat energy to produce electricity, the direct use of geothermal fluid for both heating and cooling (i.e. heat pumps), and the allowance for operating in colder climates (Lund 2013).

The use of geothermal energy in RAS has been practiced in countries such as Iceland (Ragnarsson 2014) and Alaska (Ogle, no year available). In Egypt, catfish production was achieved by using geothermal energy handled by a plate heat exchanger in a RAS (Farghally et al. 2014). Fish breeding using geothermal energy has been also successful in Japan, China, and the United States. Tilapia, salmon and trout are the most common species, but tropical fish, lobsters, shrimp, and prawns are also being farmed with geothermal energy farms (Ragnarsson 2014).
Solar energy

The sun provides a near unlimited resource for generating electricity without toxic pollution or global warming emissions. Nevertheless, there are potential environmental impacts associated with solar energy such as land use and habitat loss, water use, and the use of hazardous materials in manufacturing. There are two types of solar technologies depending on how they capture and distribute solar energy (Fuller 2007): passive solar (i.e. natural convection and direct solar absorption by the water body) or active solar (i.e. solar collector such as photovoltaic systems). In aquaculture, both active and passive technologies have been used so far. Contributions include: using passive technologies (Brown et al. 1979; Van Toever and Mackay 1980; Yuschak and Richards 1987; Provenzano and Winfield 1987; Shilo and Sarig 1989); and using active technologies (Ayles et al. 1980; Ray 1984; Plaia and Willis 1985; Fuller et al. 1998).

The use of solar energy decreases the reliance on fossil fuel for RAS energy use, especially for farms requiring a considerable amount heating. There are a few examples of using solar panels: (I) an experiment in the Canadian hatchery industry for Atlantic salmon and rainbow trout production evaluated the economic viability of various water heating techniques (including oil, gas, electricity, propane, solar, and combination systems) (Carpenter 1993); (II) a simulation model using a greenhouse with and without solar collectors (Fuller 2007); and, (III) an experimental RAS project designed to rear 432 kg of trout in Canada which depended on the use of solar collectors for water temperature maintenance. Here, coupling a solar collecting system (i.e. 91% of the required heat by solar panels) to fish rearing units decreased the total energy
consumption from 14.25 to $2.31 \times 10^{-3}$ kWh/kg fish. At a commercial scale, in Canada, solar heating was integrated with a conventional propane heating system, saving around 11,500 € per year (Toner 2002). Therefore, in terms of economy, the use of solar panels has limited direct economic benefits to the producers in the near term while indirect benefits (i.e. improve environmental sustainability and social perception) are important.

*Waste heat from industry*

Waste heat from industry has been used for commercial oyster, penaeid shrimp and salmon farming; thermal effluents in culturing American lobster and; the use of thermal waste water to produce catfish in Pennsylvania (Rickard, 1998). Eel and salmonid fingerlings production using heat from power plants (Lemercier and Serene 1980; Ingebrigtsen and Torrissen 1980, respectively) and salmonid culture using hydroelectric waste heat (Sutterlin 1981; Mercer 1984) are other examples. Positive results of using waste heat from thermal electric or hydro-electric power station were obtained and it was concluded that it may offer substantial energy and cost savings to salmon aquaculture in Canada (Mercer 1984). Additionally, animal growth was satisfactory when using waste heat and water from zero discharge power plants in the Great Basin (Heckmann et al. 1984). Nevertheless, the use of waste heat has not been widely extended within the industry as there may be significant problems such as hygiene issues due to its usage. Herein, there are not updated examples or references in the bibliography regarding this type of energy source.
Other renewable energies

Hydropower is a renewable energy source based on the natural water cycle and it is the most mature, reliable and cost-effective renewable power generation technology available (Brown et al. 2011); the only large scale and cost efficient storage technology available today (IRENA 2012). Hydropower, as one of the energy sources available from the mix in the electrical grid, has been successfully used in RAS, decreasing environmental impacts and economic costs (Liu et al. 2016).

Few studies have been published about the use of biomass, wind power or tidal energy in RAS. The latest report about the potential for renewable energy usage in aquaculture presented a case study about a marine finfish RAS facility producing 200 t of turbot/halibut (Toner 2002). It was concluded that wind and wave power may be viable sources given the energy demand (13,767 kWh/week). The installation of those systems would require a large capital outlay but this could be recouped within a period of about six years.

3.3. Energy consumption and different energy sources: published data

A possible parameter used when comparing RAS systems, is the energy consumption index (i.e. kWh/kg fish). It differs by species and the RAS as it depends on factors such as location and production volume (Table 3). Overall, the range varies widely between 2.9 and 81.48 kWh/kg. Reasons for such difference may be due to the rearing stage such as smolts or grow-out (Colt et al. 2008 and Liu et al. 2016), other design parameters such as fully recirculated or partial reuse systems (Summerfelt et al. 2009) or technical choices for the regulation of the temperature (Aubin et al. 2009). A survey comparing
salmon smolt production in RAS with similar food conversion ratios (i.e. 0.9 - 1.15) from Norway and Canada (Bergheim, et al. 2013), concluded that the energy used for production differed from one country to another significantly (4.1 and 20 kW/h, respectively). Such values were similar from the ones reported by Summerfelt et al. (2004) for Norwegian RAS industry. In the Canadian RAS, the water was only aerated while recirculated but not oxygenated, which would explain the increased amount of energy used compared with the Norwegian RAS. Similarly to the Atlantic salmon smolt production in Table 3, where high amounts of oxygen were required (i.e. hatchery and smolt production stages) and supplied by liquid oxygen. The comparison between systems should not be generalized and assumptions taken should be specified. As previously mentioned, each system is different and dependent on several factors. Thus, most of the times it is very difficult to know the factors included in the studies, resulting in very different values.

*TABLE 3*
Table 3. Literature values for species, country, production volume, harvest weight, energy source, and energy consumption of various cultured products per live-weight kilo at farm gate.

<table>
<thead>
<tr>
<th>Species</th>
<th>Country</th>
<th>Production volume (Tn)</th>
<th>Harvest weight (kg)</th>
<th>Energy source</th>
<th>Energy consumption (kWh/kg fish)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbot</td>
<td>Brittany (France)</td>
<td>70</td>
<td>1.2</td>
<td>Fossil fuels</td>
<td>81.48&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Aubin et al. 2009</td>
</tr>
<tr>
<td>Artic char</td>
<td>Nova Scotia</td>
<td>46.2</td>
<td>1.5</td>
<td>Fossil fuels (77% coal)</td>
<td>22.60</td>
<td>Ayer and Tyedmers 2009</td>
</tr>
<tr>
<td>Turbot</td>
<td>Galicia (Spain)</td>
<td>3,500</td>
<td>1.0</td>
<td>Fossil fuels</td>
<td>20.03&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Iribarren et al. 2012</td>
</tr>
<tr>
<td>Atlantic salmon</td>
<td>Pacific Northwest (USA)</td>
<td>192</td>
<td>-</td>
<td>Fossil fuels (98% natural gas)</td>
<td>80.64</td>
<td>Colt et al. 2008</td>
</tr>
<tr>
<td>Trout (FCR 0.8)</td>
<td>France</td>
<td>478</td>
<td>-</td>
<td>86.6% nuclear energy</td>
<td>16.14</td>
<td>d’Orbcastel et al 2009,a,b</td>
</tr>
<tr>
<td>Trout (FCR 1.1)</td>
<td>France</td>
<td>478</td>
<td>-</td>
<td>86.6% nuclear energy</td>
<td>17.70</td>
<td>d’Orbcastel et al 2009,a,b</td>
</tr>
<tr>
<td>Rainbow trout</td>
<td>Denmark</td>
<td>1</td>
<td>-</td>
<td>Fossil fuels</td>
<td>19.60</td>
<td>Samuel-Fitwi et al 2013</td>
</tr>
<tr>
<td>Rainbow trout</td>
<td>Iran</td>
<td>1,000</td>
<td>-</td>
<td>Fossil fuels (80% natural gas)</td>
<td>8.10</td>
<td>Dekamin et al 2015</td>
</tr>
<tr>
<td>Atlantic salmon</td>
<td>USA</td>
<td>3,300</td>
<td>-</td>
<td>90% hydropower, 10% coal power</td>
<td>5.40</td>
<td>Liu et al 2016</td>
</tr>
<tr>
<td>Florida Pompano&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Florida (USA)</td>
<td>0.43</td>
<td>0.6</td>
<td>-</td>
<td>40.30</td>
<td>Pfeiffer and Riche 2011</td>
</tr>
<tr>
<td>Atlantic cod</td>
<td>Basque region (Spain)</td>
<td>-</td>
<td>1.0</td>
<td>Fossil fuels</td>
<td>29.43</td>
<td>Badiola et al 2016</td>
</tr>
<tr>
<td>Sea bass</td>
<td>Tunisia</td>
<td>2,500</td>
<td>0.4</td>
<td>Fossil fuels</td>
<td>49.16&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Jerbi et al 2012</td>
</tr>
<tr>
<td>Sea bass</td>
<td>Tunisia</td>
<td>2,500</td>
<td>0.4</td>
<td>Fossil fuels</td>
<td>78.40&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Jerbi et al 2012</td>
</tr>
<tr>
<td>Atlantic salmon</td>
<td>USA</td>
<td>11,246</td>
<td>137.0</td>
<td>-</td>
<td>19.00-26.00</td>
<td>Summerfelt et al 2009</td>
</tr>
<tr>
<td>Rainbow trout&lt;sup&gt;g&lt;/sup&gt;</td>
<td>USA</td>
<td>2,505</td>
<td>103.0</td>
<td>-</td>
<td>2.90</td>
<td>Summerfelt et al 2004</td>
</tr>
</tbody>
</table>

<sup>a</sup> takes into account feed production (11%), equipment (1%), infrastructures (1%), chemicals (1%) and energy consumption in the farm (86%)

<sup>b</sup> partial reuse system based in a hatchery working as a RAS and traditional raceway for the grow out stage

<sup>c</sup> partial reuse system (i.e. 87-89% water treated)

<sup>d</sup> partial reuse system (i.e. 80-85% water treated)
Carbon footprint

Most of the studies show that the preferred energy sources are fossil fuel based (i.e. coal and natural gas) with increased GHG emissions in comparison to renewable sources. In contrast, renewable energies clearly may decrease the greenhouse gas emission: e.g. 4.86 kWh/kg from hydropower emitted 3.73 kg CO\textsubscript{2}-eq, while 0.54 kWh/kg from coal energy emitted 7.01 kg CO\textsubscript{2}-eq (Liu et al. 2016). Nevertheless, as in the case of trout farming in France (i.e. nuclear based energy), CO\textsubscript{2} emissions were much lower than using fossil fuel based electricity resulting in higher environmental impacts such as eutrophication potential and water ecotoxicity (Aubin et al. 2009). Therefore, the location of the farm is an important parameter that may change environmental impacts. In general, RAS companies’ electricity is generated by a public utility, limiting the options of the energy source. In this manner, the unique choice would come if the company decides to generate the electricity independent from a utility company (i.e. when a public utility is unavailable or unreliable).

Figure 2 shows the results from a comparative study and a sensitivity analysis made by the authors of three different contributions taken from the literature using fossil fuels. Firstly, CO\textsubscript{2} emissions were calculated for each study, taking into account the country of location. This was the first scenario (i.e. F). After, for the sensitivity analysis, different hypothetical scenarios were created varying (in terms of %) the source of energy used in each study: (I) 20/80- fossil fuel/geothermal energy (FG); (II) 50/50 – fossil fuel/wind power (FW); and, (III) 10/90- fossil fuel/hydropower (FH). Note that these are hypothetical scenarios including assumptions taken by the authors. Thus, in the reality, the reasons for the changes in the outcome may vary. Finally, energy-related
operational costs were calculated for all four scenarios. Data sources were gathered from the bibliography and current statistical websites detailed in the figure.

*FIGURE 2*

From the emissions perspectives, there is a general linear decrease with the % of renewables incorporated in three of the cases. From an economic point of view, results are more variable but the implementation of renewable energies seems feasible in three of the countries. It is important to remark that such comparisons (Fig. 2) are simulations based on assumptions and average values from the literature (i.e. cost of energy and kg CO₂-equ/kWh). Therefore, the reality may differ by country as energy sources are very site-specific, creating diverse environmental impacts (both in quantity and severity). In geothermal development for the generation of electricity for example, about 50% of total costs are related to the identification and characterization of reservoirs which greatly varies between countries, affecting the total costs (Barbier 2002). Moreover, wind power installations for example may be onshore or offshore directly impacting CO₂ emissions (3.00E-03 to 4.50E-03 or 7.00E-03 to 2.30E-02 CO₂-eq, respectively) (Thomson and Harrison 2015).

4. **Stakeholders’ vision:**

The opinions of stakeholders are critical for the advancement of any industry and/or company. They provide the closest judgment from the consumers which are ultimately the ones dictating either success or failure. A survey (Supplementary material) was conducted to analyze the perspective of the industry regarding energy use in RAS. The
main objective was to investigate how the energy within the system is used; which is/are the energy sources (i.e. if a renewable source is used); and how much energy is used to produce the final product (i.e. kWh/kg). This would help to identify priorities for future research in order to reduce both the environmental and economic impacts of RAS. Furthermore, the analysis considered the priorities of the industry in terms of investing or not to enhance their sustainability and which energy saving measures were applied. More subjective viewpoints and experiences of the researchers and consultants would help compare and contrast diverse ideas and approaches for the future. Survey respondents were asked about which parameters influence the energy use in RAS and which types of designs would help to enhance the efficiency of the overall system. The questions were taken as a baseline but and could be modified depending on the interviewee’s expertise.

*SUPPLEMENTARY MATERIAL 1*

The questionnaire was developed for fish farms (i.e. RAS producing farms) and opinions about personal experiences were collected from researchers, consultants and manufacturers. In the framework that new technologies are gaining more importance, a wide range of communication channels (i.e. social networks, personal communication, and interviews) were used to reach different interviewees.

In total, 96 people were contacted directly or through social media like LinkedIn and Facebook. After seven months of contacting people, 10 questionnaires were returned from the industry and comments from 15 people from both university and research centers were received. Respondents were from Australia, Belgium, Bulgaria, Finland,
France, Germany, Israel, Norway, Slovenia, South Africa and USA. Species reared by survey responders included: Atlantic salmon (*Salmo salar*), pangasius (*Pangasius buchanani*), clarias (*Clarias anguillaris*), Arctic char (*Salvelinus alpinus*), pikeperch (*Sander lucioperca*), tilapia (*Oreochromis niloticus*), rainbow trout (*Oncorhynchus mykiss*), and sturgeon (*Acipenser naccarii*). The choice of such species was because they are high value, hardy in RAS, conveniently marketed, fast growers, and internationally proven species.

RAS farms differ from each other in the design, as this is dependent on the location, available resources, and biological requirements of the species reared. However, basic procedures such as monitoring certain parameters are common to all systems. Thus, in all ten farms, dissolved oxygen, temperature and pH were continuously monitored, while CO₂, TAN, NO₂ and NO₃ were measured about once per week. In cases where the energy was measured, it was done as a total value for the whole system and not for each piece of energy consuming equipment. In all cases, production buildings were isolated and two of the respondents reported covering the tanks for heat saving purposes. Most systems (80%) used oxygenation instead of aeration and CO₂ was removed by some form of aeration. Electricity was obtained from the local grid in 60% of the cases and renewable energies such as solar energy (in South Africa), biogas from a local wetland (in Finland), wind power (in Sweden) and energy from a hydroelectric plant (in Norway) were mentioned.

In relation to energy recovery systems designed/applied, one of the respondents reported exchanging heat between the incoming (i.e. make-up water) and outgoing water through a heat-exchanger. Other answers were: retaining heat based on the system’s
operation/water use; controlling the energy use of CO₂ stripping through pH/CO₂ set-points for on/off control of blowers for energy saving and; increasing the recirculation rate through the use of denitrification technologies which resulted in energy use reduction and cost savings. Moreover, using the system’s sludge for local farming purposes and producing energy for other nearby companies through a bioreactor supplied by sludge, guts from the processing stage and mortalities, were also mentioned.

Among the respondents, RAS were considered an “environmentally friendly” fish production method mainly due to: less water usage from the environment compared to other culture technologies such as flow through systems; decrease of the eutrophication potential of the outgoing water; elimination of potential disease transfer and genetic contamination of wild stocks; use of no or very little vaccines or antibiotics because of a biosecure culture environment and the possibility of reusing discharged nutrients in agriculture. Nevertheless, in practice, sustainability of the systems (i.e. economic and environmental) was considered to be uncertain and the use of energy and its environmental impact was of no concern to the respondents. In fact, concerns identified by responders included (Fig.3): identifying alternatives to fishmeal (35%); enhancing animal welfare (i.e. increased biomass production, increased survivals and reduced maturation with the subsequent decrease of product downgrades) (26%); decreasing the feed conversion ratio (23%); decreasing the use of chemicals (11%); and decreasing the use of energy and thus, created environmental impacts (5%).

*FIGURE 3*
5. Designing a RAS: towards an efficient system

The following section aims to present an optimized RAS design approach including: suggested RAS unit processes, engineered system integration and engineered equipment selections. Moreover, alternative design solutions for each system and subsystem and component are provided. Suggested solutions or alternatives given below are from authors own experience and opinion made after the study.

Setting up a RAS requires that considerations of costs, fish welfare and product quality be taken into account. Increasingly, it also involves minimizing the potential environmental impacts. Creating and/or designing an energy efficient production RAS will help save money and energy, which will inherently help achieve a sustainable (i.e. environmental, social and economic) production operation.

The design of a RAS should ensure a proper balance of the important parameters affecting water quality and fish productivity. Important general water quality parameters for cool and warm water species include water temperature, oxygen, carbon dioxide, total suspended solids, total ammonia, unionized ammonia, nitrite and nitrate. Thus, a mass balance should be done on all of those variables (i.e. at steady state: transport in of “x” + production of “x” = transport out of “x” + consumption of "x", where “x” is the studied variable) (Timmons and Ebeling 2010). Fig. 4 shows the relation between a general mass balance on a fish culture tank and the treatment device afterwards, where Q (i.e. Q, Q₀, Q₁) represents the flow of a given parameter, C (i.e. C₀, C₁, C₂) its concentration and, P its production within the fish unit in a certain point of the system.
The concentration of any of the parameters leaving the treatment device can be easily solved since the water flow in and water flow out are equal.

*FIGURE 4*

As discussed in Section 2, various unit processes (i.e. solids and waste solids removal, aeration or oxygenation, removal of nitrogenous compounds, carbon dioxide removal) and components (e.g. filters, biofilters, air stones, pumps) are used in RAS. However every RAS is different and factors such as location, species and production volumes would directly affect the overall design (Badiola et al. 2012).

Table 4 presents a relationship between water quality parameters, unit processes and design issues. Candidate technologies, systems and equipment are related to each other.

*TABLE 4*
Table 4. Relation between water quality parameters, unit processes and design issues. Candidate technologies, systems and equipment relation with each other.

<table>
<thead>
<tr>
<th>Important Water Quality and system’s general parameters</th>
<th>Unit Processes</th>
<th>Key Application Design Issues</th>
<th>Candidate Technology, Systems and Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settleable and total Suspended Solids</td>
<td>Ammonia and nitrite</td>
<td>Carbon Dioxide (CO₂)</td>
<td>Primary and secondary recirculated flow</td>
</tr>
<tr>
<td>Waste Solids Removal</td>
<td>Biofiltration (Nitrification)</td>
<td>CO₂ removal</td>
<td>Pumping</td>
</tr>
<tr>
<td>Minimize at the source</td>
<td>Critical to fish health and growth performance. Must be robust and user friendly</td>
<td>Empirical design, limited commercial equipment</td>
<td>Must couple pump selection with RAS hydraulic profile</td>
</tr>
</tbody>
</table>

Candidate Technology, Systems and Equipment:
- Settling basin
- Radial flow separator
- Particle trap
- Microscreen drum filter
- Bead filter
- Double drain tank
- Mixed rearing cells
- Packed column; Trickling filter; Rotating contactor; bead filter; Fluidized sand; Moving-bed; Micro-bead.
- CO₂ stripper with and without packed media; Surface aerator; Moving bed reactor.
- Swimming pool pumps; Centrifugal pumps; Axial flow pumps; Air lift pumps.
- Surface aerators; Air stones; Fine pore diffusers; Contact columns & cones; U-tubes; Low head oxygenator; Hooded agitators; Liquid oxygen (LOX); PSA & VSA generators.
- Foam fractionator; Surface skimmer; Bead filter; Nutrient limited biofiltration.
- Ultraviolet disinfection; Ozonation; Ozone fed foam fractionators.
- Electric resistance heat; Plate type heat exchangers; Shell & tube heat exchangers; Geothermal heat pumps & chillers; Water-cooled heat pumps & chillers; Air-cooled heat pumps & chillers; Energy recovery.
Ammonia and nitrite

Ammonia and nitrite are critical to fish health and growth performance. Biofilter characteristics determine the maintenance requirements as well as the management techniques required in the production (Badiola et al. 2012). For example, a parameter imbalance due to daily procedures (e.g. a rapid fluctuation of the ammonia or nitrite concentration during feeding hours) and/or biomass variation can affect the biofilter’s efficiency. A variety of biofilters are available commercially. For larger systems, low-head, efficiently aerated moving-bed bioreactors are the prevailing choice, while micro-bead bioreactors are a competitive, lower cost alternative (Timmons et al. 2006; Fadhil et al. 2011).

Carbon dioxide

The prediction of carbon dioxide removal rate may be difficult due to diverse factors involved (Hu et al. 2011). Currently, there is limited availability of commercial equipment for CO₂ removal. CO₂ strippers with or without packed media, surface aerators or moving bed reactors are candidate technologies. When coupled with moving-bed or micro-bead biofilters, surface aerators provide the additional aeration and CO₂ stripping required (Liu et al. 2013). A suggested solution includes a surface aerator with variable frequency control.
Water pumping

Pump selection must be done to match the RAS hydraulic profile. There are various types of pumps available (i.e. centrifugal, axial flow, air lift). In general, axial flow pumps can be more hydraulically and energy efficient. Properly selected and trimmed, low-head centrifugal pumps are needed for higher head systems. Furthermore, variable frequency control is an alternative to trimming impeller. Nevertheless, in a real production, pump selection is highly dependent on flow rate and/or head requirements. Additionally, the availability of pumps to match required flows may be limited. Thus, it is difficult to recommend a single type of pump. A suggested solution, resulted from this study, may be an axial flow pump with variable frequency control.

Dissolved oxygen

There are many candidate technologies available for oxygen addition and oxygen and electrical power costs are site specific. The only way to determine if oxygenation is cost effective is to do a detailed cost/benefit analysis. The question is whether the cost of installation and running of an oxygenation system is offset by the extra fish that can be grown during the service life of the entire system. In other words, the cost per kg of fish of oxygenation is compared to the reduced cost per kg of system depreciation (e.g. on a moderately large system, oxygenation can add about 5% to the cost per kg and can be determined to be justified). Suggested solutions are: (I) U-tubes; (II) contact cones on side-stream pumps with variable frequency control and; (III) site specific liquid oxygen or generator selection.
Dissolved and fine solids removal

Dissolved and fine solids are important to fish health and growth performance although the implementation of a specific device for their removal is not always needed. An suggested solution for an effective removal would be robust biofiltration coupled with an ozone fed foam fractionator. Note that in freshwater the foam fractionator may not be needed.

Bacterial species and colony counts

Water quality has to be optimum for fish health and growth performance which includes achieving disinfected rearing water. The high stocking densities, associated fish stress and increased nutrient loads found in RAS create an ideal environment for fish pathogens. There are diverse steps taken to reduce the risk of disease outbreaks in RAS: (I) the use of standard quarantine procedures for any fish introduced (prior to entering production tanks); (II) reduce the pathogen load introduced by treating the source water and; (III) the disinfection of effluent waters before introduction to the environment to prevent the translocation of exotic diseases.

Some types of disinfection are usually employed such as ultraviolet disinfection units and/or ozonators where a significant level of disinfection is achieved (Kingsley et al. 2008). A suggested model or solution would be the use of ozone fed foam fractionators where bacterial reduction achieved is moderate and bacteria are physically removed by the fractionator (Phillips et al. 2004). Nevertheless, the use of disinfection as part of the recycle loop should be applied in specific situations, as it could be counterproductive in
general use. In smolts facilities, for example, large UV systems are applied; minimizing disease risk may come at the expense of the extra energy required for its functioning.

Temperature

Heating and/or cooling of the rearing water is achieved by different equipment: electric resistance heaters, plate type heat exchangers, shell and tube heat exchangers, geothermal heat pumps and chillers, water-cooled heat pumps and chillers, air-cooled heat pumps and chillers, energy recovery. Apart from this, site selection has tremendous cost implications in temperature’s control, energy costs and shipping costs directly linked with the species produced.

6. Concluding remarks:

RAS designs are being developed and improved by incorporating new technologies (e.g. Piedrahita et al. 1996; van Rijn 1996; Cripps and Bergheim 2000; Summerfelt and Penne 2005; Eding et al. 2006; Summerfelt 2006). However, studies describing new technologies typically do not include considerations of energy use by the technologies or of their impact on total energy consumption and system efficiency (Badiola et al. 2012). In the past, the statement “sustainable production”, did not necessarily include energy use considerations (e.g. Crab et al. 2007; Tal et al. 2009). Nevertheless, excessive energy use generates significant economic and environmental impacts. Thus, in order to emphasize the advantages provided by RAS, energy consumption should be minimized relative to production (i.e. kWh/kg fish produced).
The challenge for designers is to develop systems that minimize production cost per unit cost of production (including capital and operational costs). Optimal system configuration, from economic (i.e. pumping cost minimization) and environmental points of view, have yet to be defined and studied according to each farming context (i.e. the energy use due to feed, electricity and oxygen consumption is system-dependent). According to the specific context of the farm, a compromise has to be found between water dependence, waste emission, energy consumption and productivity in order to orient the system towards economic and environmentally sustainable production.

In such context, and in accordance to the extensive literature review and interviews made by the authors of the present contribution, energy use in RAS could be reduced by:

- Investing in an area where on average the optimum environmental conditions (e.g. temperature) are naturally available.
- Meeting overall needs of the species of concern while minimizing energy costs.
- Improving both the system design and management of airlifts and bio-filters.

Finding a compromise between: an optimal design for water circulation and water oxygenation of the airlift and the backwash and operation of the bio-filters.

- Minimizing height differences between RAS compartments, i.e. low head RAS (RAS should be designed to avoid lifting of the water, when possible).
- Land or building prices may outweigh the advantage of spreading out horizontally. However, more "vertical" systems may come at the expense of higher pumping costs. An alternative may be the use of deeper tanks. They provide higher
production volumes in the same footprint not requiring any extra pumping head when buried into the ground.

The electricity generation obtained from fossil fuels causes local and global environmental problems. Thus, the use of renewable energy sources for RAS farming needs to be thoroughly assessed for its suitability in each particular situation. An economic analysis needs to compare the cost of connection as well as the use of alternative sources, considering: the consequences of power outages; the fact that a facility is not totally relying on an intermittent renewable energy source and; the accessibility of a possible back-up. Thus, production’s audits including Life Cycle Assessments and integrating energy audits would be the way towards a cost-effective industry (Badiola et al. 2017).

Acknowledgments

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Figure captions:

Fig. 1 Worldwide countries ranged according to the number of RAS companies in each country. Information updated from Martins et al. 2010; Badiola et al. 2012, 2014 and Dalsgaard et al. 2013 after a worldwide research made by the authors through personal communication and social networking during the last 4 years.
Fig. 2 Comparison of three different studies analyzing CO₂ emissions by different energy sources and operational costs created by the energy consumption in each of them (F: First scenario; FG: Fossil fuel/Geothermal energy; FW: Fossil fuel/Wind power; FH: Fossil fuel/Hydropower).

Fig. 3 Concerns around RAS production identified by responders of the present study.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0</td>
<td>Water flow</td>
<td>l/s</td>
</tr>
<tr>
<td>Q1</td>
<td>Treated water’s flow</td>
<td>l/s</td>
</tr>
<tr>
<td>C0</td>
<td>Incoming concentration of a parameter</td>
<td>mg/l</td>
</tr>
<tr>
<td>C1</td>
<td>Outgoing concentration of a parameter</td>
<td>mg/l</td>
</tr>
<tr>
<td>C2</td>
<td>Outgoing concentration of a parameter after treatment</td>
<td>mg/l</td>
</tr>
<tr>
<td>Q</td>
<td>Flow of a given parameter</td>
<td>l/s</td>
</tr>
<tr>
<td>Cin</td>
<td>Incoming concentration of a given parameter</td>
<td>mg/l</td>
</tr>
<tr>
<td>Cout</td>
<td>Outgoing concentration of a given parameter</td>
<td>mg/l</td>
</tr>
<tr>
<td>P</td>
<td>Production of a given parameter with the fish unit</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4.** A general mass balance of a production tank and a general treatment device (Timmons and Ebeling 2010)
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