Aquaculture and energy use: a desk-top study

Sara Hornborg and Friederike Ziegler

Introduction

Global aquaculture is highly diverse. It encompasses a broad range of species– approximately 600 animals and plants; operates in fresh, brackish and marine waters; as monocultures or poly-cultures and can have a wide range of production intensities (FAO 2014). The bulk of aquaculture production is inland finfish production, contributing to 58 % of global production figures. Molluscs constitute the second group of species in terms of production volume (23%), followed by crustaceans (10%) and marine finfish (8%).

At present nearly half of all fish for human consumption is provided by aquaculture, and it is the fastest growing animal food-producing sector in the world (FAO 2014). Given the limits of natural fish production, and as seafood consumption per capita is on the rise, increase in aquaculture production has repeatedly been seen as vital to bridge the gap between growing seafood demand and limited supply (Merino et al. 2012). Global production is however at present highly un-even, as Asia produces 88% of the global supply. As for single countries, China dominates in terms of contribution to production volume in all species groups except mariculture of finfish, where Norway dominates.

There are also concerns of varying urgency associated with current aquaculture production forms. These comprise of problems relating to spread of disease and parasites, ecological and genetic impacts from escapees, release of chemicals into water, eutrophication, energy use, feed demand (with various ecological costs depending on feed formula), etc. (reviewed in Ford et al. 2012). To meet current and future demand for aquaculture commodities, it is thus seen as imperative that growth can be accomplished while utilizing less resources and reducing environmental impacts (World Bank 2013). It is therefore of vital importance to identify and promote the most resource-efficient forms of aquaculture for the sector to grow in the most sustainable manner.

The focus of this report is energy use in a life cycle perspective, i.e. per product. Aquaculture commodities have been shown to be in the mid-range in terms of energy intensity relative to agriculture, livestock and fisheries (Pelletier et al. 2011). If different methods of producing the same species have different energy demand per unit produced, policies supporting these production forms could be the next step to reduce energy use. If, on the other hand, energy consumption of a species is essentially fixed in relation to output, policies targeting energy efficiency are less useful or justified but may instead require polices related to consumption patterns. In addition, a comparison between aquaculture products and other forms of food production is made to put these figures into a wider perspective. Furthermore, trade-offs between energy efficiency and other environmental concerns will also be touched upon in brief.

Aim of the study:

To review how, and how much, energy is used in aquaculture production and whether or not energy use is defined by the choice of species or production technology. Comparisons are made between species, systems and other forms of protein production.

Methods

The report is based on a screening of primarily published energy analyses and more or less complete Life Cycle Assessments (LCAs) of aquaculture systems. LCAs are useful as tools to identify hot-spots and improvement potentials, and to avoid a shift in environmental burden between production stages or different impacts. The different values for energy demand are given in MJ-equivalents (i.e. all energy forms are converted and combined into a single energy demand metric) and are predominantly reported per wet weight at farm gate (i.e. ready to be distributed from production site) unless stated differently.

It is however important to note that figures in this report should be seen as indicative and not directly comparable. It is of vital importance to acknowledge that methodological choices in the different studies highly influences the results and what may be interpreted from them (reviewed in Henriksson et al. 2012). One important factor is how allocation has been done in the various studies, i.e. how upstream energy use has been split between co-products. Other factors influencing the absolute values are choice of functional unit, i.e. assessment unit, and system boundaries of the studies, i.e. what has been included in the assessment and not. In many cases, results were not presented transparently enough to draw conclusions on how the methodological choices do influence the results. To minimize these constraints when comparing energy use from aquaculture products with other protein sources, the approach has been to use comparisons within studies rather than between.

It should also be acknowledged that the industry is rapidly changing and studies are quickly getting outdated. Especially rearing techniques, such as development of feed formula and feeding technology, change and highly influence results.

Key questions are:

a) Is energy use fixed by the choice of species or production technology?

b) What is the amount of embodied energy in aquaculture products compared with that of other types of foods?

Results

Global production

A rough sketch emerges if the FAO species groups are matched with early estimates on energy consumption per energetic output (Table 1). Pond aquaculture of finfish dominates in contribution to production volume while also being the seemingly most energy efficient production form. The smallest production volume, crustaceans, has the highest energy demands. It should be noted that all estimates are restricted by which systems that have been studied, and culture techniques have also improved over time.

Table 1. Production volumes per species groups with main species cultured and estimates on energy use. Note that these figures should be seen as indicative. Based on FAO (2012; 2014) and Troell et al. (2004).

Species group	Production types[1]	Volume (million tonnes)	Main species	Energy use per protein energy output (J/J)
Finfish, inland aquaculture	Ponds at different intensities	38.6	Carps	1-25
Finfish, mariculture	Marine cages	5.6	Atlantic salmon	40-50
Molluscs	Long line, tanks	15	Clams and cockles; oysters; mussels	10-136
Crustaceans	Ponds, tanks	6.4	White leg shrimp	40-480
Other species	n/a	0.86	Amphibians and reptiles	n/a
Algae	n/a	23.8	*Kappaphycus alvarezii*; *Eucheuma* spp.; *Laminaria japonica*	n/a

Assessing energy demand in aquaculture is challenging. Energy flows when producing feed is a complex, tree-like structure; commercial feed production involves many different subsystems for feed components based both on agriculture and fisheries that are linked together in the feed formula. The LCA framework is useful as an accounting system, mapping the contribution of all parts to the sum of the end product. However, there are also methodological challenges when assessing each sub-system in isolation, each with various by-products being produced. Still, one of the main benefits of applying the LCA methodology on aquaculture systems is that it tries to takes into account these aspects of the production system. The output is the cumulative result of all these differences, to the extent that is possible.

This said, LCA research has found important contributing factors for the vast ranges of energy requirements found for the different species groups summarized in table 1. As an example, there may be major differences between farms. Henriksson et al. (2014) found that the energy required to produce one tonne of tilapia in China (sample size 84 farm sites) was on average 3535 MJ for an integrated pig-tilapia farm – with a standard deviation of 3532 MJ! Factors affecting energy use in aquaculture will be examined in the next section.

[1] Systems that are considered in the energy estimates in this table

Factors influencing the energy use of aquaculture

The following section identifies separate factors that have an influence on energy efficiency. It is however important to note, that most of these singled-out factors are co-dependent.

Choice of species

If the cultured species require input of feed, feed production has been shown to dominate energy use in a range of aquaculture systems, as well as many other environmental impacts (Troell et al. 2004). The dominance of feed production to overall energy demand has been shown both for more herbivorous species such as common carp and tilapia in Asia (Mungkung et al. 2013) and carnivorous species, such as rainbow trout, sea-bass and salmon (Aubin et al. 2009; Pelletier et al. 2009). It has been found that approximately 90 % of the energy use in salmon farming in open cages originates from feed provision (e.g. Tyedmers et al. 2007, Ayer & Tyedmers 2009). However, the relative percentage to which extent energy use is attributed to feed use varies with production system (see section on Choice of production system); in rainbow trout production from a flow-through system in France, energy use for feed production accounted for 52% of the total energy use (Papatryphon et al. 2003).

Species-specific feed requirements and growth rate put constraints on how far energy efficiency can go for that particular species. Feed conversion ratio has been found to influence energy efficiency, in particular in intensive systems (e.g. Grönroos et al. 2006; Aubin et al. 2009), due to the important contribution from feed production to total energy use of the system. Carnivorous species additionally require higher protein content in the feed than herbivorous species and often a higher proportion of marine inputs in order to maintain product quality e.g. in terms of content of omega-3 fatty acids. This affects the energy use of the feed.

However, it should be advocated for to, in parallel to trophic level, studying the amount of feed required of the farmed species. Pelletier and Tyedmers (2010) showed that even if the feed used in tilapia systems may be more environmentally preferable per kilo feed produced, a higher amount is needed to grow one kilo of tilapia than what is required to grow one kilo of salmon with a more resource demanding feed (per kilo feed). This outbalances benefits of lower trophic level species.

Fewer LCAs have been made on farming practices without inputs of feed and medication, such as bivalves. For farming of blue mussels (*Mytilus edulis*), the total energy demand in Norwegian farming has been estimated to be 3 MJ per kilo (Winther et al. 2009); the energy use per kilo washed and sorted mussels may be almost twice that live unsorted mussel. This is the result of that there is a large proportion of small and crushed mussels in the harvested mass, going to waste. The energy profile is also affected by a low edible content (24%). In Scottish mussel farming, energy requirements were found to be lower, but with considerable variability between farm sites (Meyhoff Fry 2011). There may also be a high energy demand of purification of mussels, as seen in Spanish mussel farming on rafts (Iribarren et al. 2010).

If the species does not breed in captivity, collection of broodstock in the wild could also prove to be energy demanding (Mungkung et al. 2006). On the other hand, smolt production to Norwegian salmon has been found to also be an energy demanding subsystem; still, it has less influence on total energy demand of salmon (Winther et al. 2009).

Ayer and Tyedmers (2009) also found a major difference in mortality rate between Arctic char and Atlantic salmon. Whether this was due to differences between grow-out systems (Arctic char was reared in a land-based re-circulating system) or a difference between the two species or farming know-how was left unanswered in the study. All in all, species-specific energy efficiency cannot be singled-out without evaluating the production system itself (see section on Choice of production system).

Choice of species: Scope for improvement

Species-specific feed requirements, growth and mortality rate are important determinants of energy efficiency, as feed production is highly energy demanding. Choose species with no or little feed requirements, keep mortality rates and feed conversion ratio low and growth rate high. For non-fed species, improvement options consist of minimizing product losses and keeping energy demand for vessels operating the site low, i.e. focus on the production system. Still, to summarize, due to the important contribution of feed to the total energy demand of the farming system, there are certain limits to how low a certain species could go in terms of energy efficiency; Norwegian culture for salmon would typically require 28 MJ per kilo live-weight, while blue mussels would be in the range of 3 MJ respectively (Winther et al. 2009).

Choice of feed

The general dominant contribution of feed production to overall energy use comes from the dependence of agricultural and fishery stages. These activities require a relatively large amount of energy. Still, optimising the feed formula or feed conversion ratio would lead to major reductions in overall energy use.

It has been found that improving feed conversion ratio and changing feed formula could decrease energy use from 33 MJ to 25 MJ per kilo of un-gutted rainbow trout in Finland (Grönroos et al. 2006). Similarly, Pelletier & Tyedmers (2007) showed that the energy use per kilo feed to grow one kilo of Atlantic salmon varied between 13 to 35 MJ depending on feed formula. It was found that he edible protein energy return on industrial energy investment (EROI) of farmed salmon may be 117% when using wheat, 91% for corn and only 17 % for poultry by-products in the feed.

There are also major differences in energy efficiency between marine inputs. Using by-product fish meals and oils from herring processing may not be the most energy efficient option compared to dedicated reduction fisheries, such as anchoveta or menhaden, due to low meal and oil yield rates in combination with higher fuel intensities (Pelletier & Tyedmers 2007). As a result, the least efficient crop-based inputs (such as corn, soy and wheat gluten meal) can be more energy-intensive than the most energy-efficient marine inputs (such as meals and oils based on anchoveta and menhaden). This finding was also supported by Pelletier et al. (2009). Papatryphon et al. (2004) also found that completely excluding fish meal and oil content would not represent the most energy efficient diet in rainbow trout production. In line with this reasoning, Troell et al. (2004) argued that different countries have various degree of industrialized agriculture which influences the energy use of the feed formula of agricultural origin. The relative contribution to energy use from agriculture, processing or transports also varies between ingredients and with distribution patterns (Pelletier & Tyedmers 2010).

However, general energy reductions could be made from increasing crop-based ingredients in feed, but less so for opting for organic ingredients. Even though organic crop ingredients may have lower associated impacts, the most important reduction of energy use and environmental impacts from feed production may be to just increase crop based ingredients in the feed formula (Pelletier & Tyedmers 2007). Shrimp farms in Vietnam also showed marginal differences between certified and non-certified farms in terms environmental performance of life cycle impacts (Jonell & Henriksson, manuscript).

It should also be acknowledged that the continuous search for new feed ingredients than fisheries-derived is linked to that there are limits of natural fish production; aquaculture dependence of capture fisheries is a hot topic (Allsopp et al. 2008). Given that the more carnivorous species depend more on capture fisheries (Tacon et al. 2009), and that there is a tendency to increasingly farm higher trophic level species, i.e. carnivorous (Stergiou et al. 2009), this has caused concern of future sustainability of the sector. In a sense, the farming of different species could be seen to, besides using input of energy, also make use of different amount of emergy, i.e. require different amounts of ecosystem energy derived from photosynthesis (Wilfart et al. 2013).

There are also major differences between countries in terms of production of the same species, mainly originating in feeding practises (Table 2). As an example, Tilapia grown in Thailand has in comparison to Chinese production been shown to use 50% more fishmeal, and from more energy-intensive sources (Henriksson et al. 2014). There is also a greater extent of co-production with carp in China. Salmon production may also vary in terms of energy efficiency between countries (Pelletier et al. 2009).

In terms of utilization of global fish meal production, marine shrimp culture is at the top (27%), whereas salmon production requires nearly 14% (FAO 2012). As for fish oil, however, salmon is in the top (37 %) whereas marine shrimp only use 13% respectively. Note that out of total aquaculture production volume, crustaceans contribute to 10% and salmon merely 8 % respectively.

Choice of feed: Scope for improvement

Feed production contributes highly to energy demand of aquaculture of fed species. A rule of thumb would be to minimize feed input per output production and optimize feed formula composition. Different countries may also have different legislation with regard to which feed inputs are permitted to use in feeds for aquaculture (e.g. poultry by-products are permitted in Canada and Chile, but not in Norway or the EU). This issue could be interesting to further study the effects from. There are also most likely differences in experience and know-how of culture techniques, as well as different farming conditions in different areas (e.g. climate).

Choice of production systems

The grow-out system also influences overall energy efficiency, as already mentioned in the earlier sections on choices of species and feed formula. Two main overarching production forms can be seen, fully commercial/industrial versus more rural/subsistence-based activities (Troell et al. 2004). These categories can then further be separated by intensity based on resource input and production rate: extensive, semi-intensive and intensive. Intensive practices typically use tanks, ponds and open-water pens to culture carnivorous finfish (e.g. salmon, seabass, halibut, eel) and are almost exclusively reliant on commercial feeds. Semi-intensive and extensive practices use commercial feeds to various degrees, but may also use fertilizers to enhance pond productivity. Herbivorous fish and invertebrates are most often produced using these systems.

In terms of intensive production systems, a broad range of closed systems have been developed over time: marine floating bags, funnels under net pens, land-based saltwater flow-through systems and land-based freshwater or marine recirculating systems (Grönroos et al. 2006; Ayer & Tyedmers 2009). In these systems, additional water additives and mechanical equipment are also required, such as addition of liquid oxygen, heating, chilling, water purification and more. The extent of artificial enhancement of the system depends on the degree of closed-containment and location of grow-out facility. The different solutions also vary vastly in terms of stocking density and production rates, which is reflected in energy use, feed requirements and infrastructure per tonne of live-weight seafood.

Aubin et al. (2009) compared three different intensive systems: flow-through for rainbow trout (*Oncorhynchus mykiss*), open cage for seabass (*Dicentrarchus labrax*) and an inland re-circulating system for turbot (*Scophtalmus maximus*). In the cage system, feed had the dominating contribution to energy demand (72%). As the system gets more artificial, the contribution of feed to the overall energy demand is of less importance. Feed production only accounted for 40% of the energy use in the flow-through system, whereas 47% of demand came from energy carriers used on the farm site. In this system, an additional 7% of the total energy use came from use of chemicals (liquid oxygen). For the re-circulating system, the main contribution to energy use came from energy consumption on the farm (86%), while feed production contributed only by 11%. The farming system thus affects both the relative contribution and absolute values of energy demand of the cultured species.

This is confirmed by a study of rainbow trout systems in Finland which compared the influence from various feed conversion ratios and feed formulas, but also the commonly used net pens to other, less common, systems: closed floating cage, funnel and a land-based marine farm (Grönroos et al. 2006). With the same feed formula and feed conversion ratio, the typical net cage production required 33 MJ per kilo un-gutted trout whereas the funnel system was estimated to require 37 MJ, the closed floating cage 55 MJ and the land-based marine farm 110 MJ, respectively.

There are options to reduce energy demand of the system. In a study of an indoor re-circulated farming system (RAS) for shrimp in the U.S, energy use was highly influenced by farming location (Sun 2009). The energy use from circulating the water in closed-containment systems could be substantial depending on the grow-out system’s location in relation to sea level and influence from low-and high tide (Ayer & Tyedmers 2009).

However, different systems have intrinsic constraints to energy efficiency; there are different scopes for improvement. A shift from conventional pens to land-based systems would require substantially greater resources, whereas a shift to marine bag systems these differences would be more marginal (Ayer & Tyedmers 2009). In the Spanish mussel farms, improvement in energy efficiency may be achieved from reducing diesel demand of vessels operating on the farm site (Iribarren 2010).

Energy use in extensive systems is less known. Up to date, more LCA studies have been done on intensive farming systems than on more extensive ones (Table 2). As feed formula and amount required has been shown to be of great importance to energy efficiency, it could be argued that extensive systems with less feed input are most probably favourable in terms of energy efficiency.

Still, it is important to acknowledge that there is rather a range of intensities between the two extremes, intensive and extensive systems, with farming intensity shown to vary substantially for the same species (Henriksson et al. 2014). Higher stocking densities and feed input require more external input of energy to combat deteriorating water quality. As an example, shrimp systems in Asia can either make use of passive water exchange or be fully dependent on active water pumping. This said, intensive culture of white-leg shrimp in China can be almost twice as energy demanding as semi-intensive systems of the same species per kilo output (Cao et al. 2011). One extremely energy demanding practice is using paddle-wheels in shrimp farms to aerate the water; energy requirements for these can be as high as 10 800-14 400 MJ per kilogram shrimp produced (Henriksson et al. 2014). Integrated farming of pigs and tilapia in China has been shown to have higher energy use than non-integrated poly-cultures of the same species (Henriksson et al. 2014). This could be a result of greater need for aeration, which requires energy-demanding paddle-wheels. It could also be a result of the stocking density in the pig-integrated system being almost twice as large as in the most energy efficient practice, reservoir based poly-culture.

Feed production is most important to overall impacts of tilapia systems, but lake-based culture has been found to require greater inputs of feed than is required for pond-based production (Pelletier & Tyedmers 2010). However, on-farm energy use is substantially lower for lake-based culture, as aeration is not required. As a result, pond-based tilapia culture has almost 50% higher energy demand per tonne of tilapia produced; feed input determines to a lesser extent energy use of the pond system than for the lake system accordingly.

In addition, even if an extensive poly-culture does not require industrially produced feed, it may instead require energy use to collect prey for the cultured species. In a Filipino fish/prawn poly-culture, the collection of snails for feeding the prawns could in turn lead to energy inefficiencies depending on prey availability in the surrounding area (Baruthio et al. 2008).

Choice of production system: Scope for improvement

On top of feed production, the production system sets the frame for the absolute values for energy demand of the system. If the production system is to be made more energy efficient, there are different scopes for improvement. Careful planning before establishment is also useful from an energy efficiency perspective.

Table 2. Literature values for energy use of various cultured products per live-weight kilo at farm gate. Note that these figures should be compared with caution as different methodological approaches are behind estimates.

Species	System	Category	Energy use (MJ)	Source
Turbot ***Scophtalmus maximus***	Re-circulating, land-based	Intensive	291	Aubin et al. (2009)
Sea-bass ***Dicentrarchus labrax***	Cages, marine	Intensive	55	Aubin et al. (2009)
Rainbow trout ***Oncorhynchus mykiss***	Flow-through, freshwater	Intensive	78	Aubin et al. (2009)
Rainbow trout ***Oncorhynchus mykiss***	Flow-through, freshwater	Intensive	30-78	Papatryphon et al. (2003)
Rainbow trout ***Oncorhynchus mykiss***	Closed floating cage	Intensive	55	Grönroos et al. (2006)
Rainbow trout ***Oncorhynchus mykiss***	Net-cage	Intensive	33	Grönroos et al. (2006)
Atlantic salmon ***Salmo salar***	Norway	Intensive	28	Ziegler et al. (2013)
Atlantic salmon ***Salmo salar***	Norway	Intensive	26	Pelletier et al. (2009)
Atlantic salmon ***Salmo salar***	U.K.	Intensive	48	Pelletier et al. (2009)
Atlantic salmon ***Salmo salar***	Chile	Intensive	33	Pelletier et al. (2009)
Atlantic salmon ***Salmo salar***	Canada	Intensive	31	Pelletier et al. (2009)
Atlantic salmon ***Salmo salar***	Net-pen, marine	Intensive	27	Ayer & Tyedmers (2009)
Atlantic salmon	Floating bag,	Intensive	33	Ayer & Tyedmers

Salmo salar	marine			(2009)
Atlantic salmon ***Salmo salar***	Flow-through, land-based saltwater	Intensive	98	Ayer & Tyedmers (2009)
Arctic char ***Salmo alpinus***	Re-circulating, land-based freshwater	Intensive	353	Ayer & Tyedmers (2009)
Tilapia ***Oreochromis niloticus***	Lake-based	Intensive	18	Pelletier & Tyedmers (2010)
Tilapia ***Oreochromis niloticus***	Pond-based	Intensive	27	Pelletier & Tyedmers (2010)
Striped catfish ***Pangasianodon hypophthalmus***	Pond-based	Intensive	13	Bosma et al. (2011)
White-leg shrimp ***Litopenaeus vannamei***	Ponds	Intensive	62	Cao et al. (2011)
White-leg shrimp ***Litopenaeus vannamei***	Ponds	Semi-intensive	34	Cao et al. (2011)
Tiger prawn (*Penaeus monodon*), crab (*Scylla serrata/olivacea*), milkfish (*Chanos chanos*) and tilapia (*Oerochromis niloticus*)	Poly-culture	Extensive	46[2]	Baruthio et al. (2008)
Galician mussels (*Mytilus galloprovincialis*)	Rafts	Extensive	3	Iribarren 2010
Blue mussels (*Mytilus edulis*)	Longline	Extensive	3	Winther et al. (2009)/Ziegler et

[2] Non-renewable energy use

				al. (2013)
Blue mussels (*Mytilus edulis*)	Longline	Extensive	1	Meyhoff Fry (2011)
Oysters	Bag and trestle	Extensive	4	Meyhoff Fry (2011)

Trade-offs with energy efficiency

There are also trade-offs between energy efficiency and other environmental aspects of aquaculture. Limited fish resources catalyse the turning away from these inputs in feed formula. Globally, the use of capture fisheries for fishmeal has decreased, and 35 % of the fish meal production in 2012 came from fish residues (FAO 2014). Utilizing by-products such as trimmings from the capture fisheries industry may be seen as favourable instead of this valuable and limited resource going to waste. However, given the relatively high energy efficiency of reduction fisheries compared to the fisheries targeting fish for consumption from which the trimmings originate, this may negatively influence energy efficiency of the feed formula (Tyedmers et al. 2007).

In addition, energy requirements when using low-value fish as feed directly has been found to be lower than that of pelleted feeds in marine cage farming in Asia– but the "fish in, fish out" ratio for the production was about three times lower with pellet feeds than with low-value fish (FAO 2014). In a thorough review of Asian aquaculture by Henriksson et al. (2014), turning to commercial feeds in less industrial farming practices was seen as an improvement potential; non-commercial and farm-made feeds were found to be less environmentally and economically favourable, as well as some feeding practices also contribute to poor water quality which then needs more industrial input to combat.

As already mentioned, re-circulating systems are often much more energy intensive than production in open cages. A re-circulating system will lead to considerably higher overall resource demand and emissions, including higher feed requirements if the mortality rate of the cultured species is high (Ayer and Tyedmers 2009). However, the same system may on the other hand be superior in terms of eutrophying emissions, and it is much easier to control escapees, disease transmission and more. Rearing in tanks makes it easier to monitor and control production, such as controlling number of fish, growth and feeding efficiency; even if a re-circulating system can have five times higher energy requirements than an open cage system, the open cage system can have a lower feed efficiency (Aubin et al. 2009). Also, in an indoor re-circulating farming system (RAS) for shrimp in the U.S., it was found that compared to a flow-through system, the RAS system required 1.4 times more energy but used 70% less water (Sun 2009). All in all, if the re-circulating system works in terms of control of fish mortality, re-circulating systems offer many benefits even if they are more energy demanding. Developing poly-culture systems for intensive production systems, such as culturing salmon together with algae, may also be an option to curb nutrient release and capture carbon.

Even if extensive systems are favourable in terms of being less energy-intensive, land-use is of growing concern for a growing industry. Due to side-effects of transforming more mangrove areas in Asia into aquaculture systems, one important being net effect on greenhouse gas emissions from removing the mangrove, aquaculture production has been recommended to not expand (Henriksson et al. 2014). Instead, intensification of some production systems would be a better option if production is to increase.

Finally, not only the energy demand varies between systems, but also the energy source. This aspect may be of greater importance for resulting emissions than the energy requirement itself. In a recirculating system, 80% of impacts could be associated to on-site electricity demand (Ayer & Tyedmers 2009). The same study also showed that the studied net-pen system had a lower energy demand, but used small amounts of fossil fuel– whereas closed-containment systems primarily operated with electricity, but with substantially greater energy requirements per production output. Energy requirements based on coal and other fossil resources are associated with greenhouse gas emissions, while nuclear-based energy e.g. leads to emissions of ionizing radiation. Choosing the energy source causing least environmental impacts (i.e. renewable sources) can be especially important for highly energy consuming activities such as closed containment aquaculture.

Energy use in aquaculture in comparison to other production systems

If compared in terms of edible protein energy output per input of industrial energy (EROI), aquaculture commodities can be in both the lowest and highest range (Tyedmers et al. 2007; Troell et al. 2004). The most rewarding protein production in terms of energy efficiency is extensive culture of carp and purse-seining for herring. Carp farming in ponds is in fact in the range of vegetable crops, whereas lobster culture in tanks has been found to be in the top range, requiring over 100 times as much energy as carp. Salmon, on the other hand, is in the higher range in terms of energy use compared to other food commodities (Table 3).

Given the benefits of better ecological efficiency and less environmental impacts for many aquaculture systems than many other animal food production systems, Hall et al. (2011) argue that the relative benefits of policies promoting fish farming over other forms of livestock production should be considered.

Still, interestingly, a comparison of ecological footprints between salmon production systems showed that the eco-efficiency was poorer for farmed than fished (Tyedmers 2000). The same applies for farmed and fished mussels; the fuel demand to fish mussels has been estimated to be lower than the input required for farming mussels per kilo of product (Iribarren 2010).

Table 3. Comparison of energy use (MJ) between different production systems. Please note that there are different methodological approaches behind these results, so they should merely be seen as indicative.

Unit	Salmon	Wheat	Chicken	Pork	Herring	Beef	Cod	Source
Per kg bone-free meat				13-42		5-44		Sonesson et al. 2010 (and references therein)
Per kg fillet	65		55				65	Ellingsen & Aanondsen 2006
Per edible kg	40		29	41	7	79	27	Winther et al. 2009 (and references therein)
Per kilo (unspecified)	31	2.6	17	23	0.9-6.9	32	4.6-92	Pelletier et al. 2011

Future perspectives

It has been estimated that energy demand from global aquaculture will increase from roughly 4 600 million GJ to 10 700 million GJ as a result of higher demand for fish in 2050 (Mungkung et al. 2014). Other impacts associated to increasing production from 60 Mt to 140 Mt, such as greenhouse gas emissions per unit produced, were seen to only marginally decrease from intensification of pond farming, improving feed conversion ratios or shifting towards higher proportion of freshwater finfish farming compared to the baseline scenario of business-as-usual.

However, switching to renewable energy would allow the sector to expand production without increasing present level of greenhouse gas emissions. Combined with the other mentioned improvement potentials in terms of best practice of farming, greenhouse gas emissions were even estimated to decrease compare to present levels. As for energy demand, intensification was according to Mungkung et al. (2014) seen to be the most energy demanding option; use of renewable energy had the lowest energy demand, in particular in combination with other best practices identified.

There are also post-harvest energy improvements to be made in some supply chains. Freezers at processing plants in Asia have been found to be hot spots in terms of energy consumption beyond the farm (Henriksson et al. 2014). This is linked to poor technology, as the energy use can vary between 1 440 MJ per kilo shrimp produced in Thailand to 9 000 MJ in Bangladesh.

Discussion

In general, results show that in systems with carnivorous fish, provision of feed highly influences the energy use and general environmental performance of aquaculture systems. Energy efficiency in aquaculture may therefore improve by improving the feed production and increased production of species less dependent on high-protein content feed. In 2008, nearly half of global aquaculture production (including aquatic plants) was estimated to be dependent on external feed sources (FAO 2010). The share of non-fed species of the total farmed production for food has shown a declining trend, from 34% in 2010 to 31% in 2012 (FAO 2014). Therefore, growth for culture of non-fed species requires a shift in the global development.

Different production forms and species farmed show different improvement potentials and means required to do so. For farmed carnivourous species such as salmon in net-pens, improving feed formula would be more important as well as improving feed conversion ratios (Pelletier et al. 2009). For blue mussels, increasing yield, use of by-products, and reducing fuel consumption for vessels performing maintenance and harvesting would be the options to improve energy efficiency (Meyhoff Fry 2009; Winther et al. 2009). For more closed and land-based farming systems for carnivourous species, the location of farm site and rearing techniques are more important to optimize to reduce energy consumption (Aubin et al. 2009; Ayer & Tyedmers 2009).

It should however be noted that there are still methodological challenges to compare energy efficiencies between cultured species, systems and relative to other food commodities. Assumptions made concerning energy use from both feed provision and on-site demand have at the same time been identified to highly influence results (Hall et al. 2011). There is also a considerable variability between farm sites (Henriksson et al. 2014; Meyhoff Fry 2009). Therefore, more data needs to be collected in order to get a better understanding of differences between systems and the impacts from different feed inputs in a rapidly changing and growing sector.

However, on the positive side, there are only 15 countries producing over 92% of the cultured fish volume; of these countries, 11 were located in Asia-Pacific region (FAO 2010). This implies that increasing energy efficiency of global aquaculture production could be made by focusing on a few nations. As there are also major differences in production of the same species between different countries, opting for the best-available technology and knowledge transfer between countries would foster energy reductions of the whole sector, in both established and new countries. Larger aquaculture enterprises may also have dedicated projects on how to reduce energy use, such as efficient personnel transportation (Marine Harvest Annual Report 2013). LCA based evaluations may in this context offer important insights in where to target the most important activities to reduce, among others, energy consumption.

Last, energy use is only one aspect of sustainability. It should e.g. be acknowledged that energy use do not have a linear relationship with estimates for greenhouse gas emissions. In agriculture as an example, there are several gases involved (such as methane and nitrous oxide) that are more potent to cause climate change than carbon dioxide. The total carbon footprint in terms of contribution to climate change for aquaculture commodities thus varies with feed formula, energy source and potential release of other more climate forcing gases than carbon dioxide.

Recommendations for energy reductions for aquaculture products

- *Minimize feed requirement.*
  Use techniques which minimize feed loss and optimize growth, or culture species without feed requirement.
- *Increase crop ingredients in feed formula.*
  Vegetable components are often more energy efficient, even if there are exceptions. However, in production of carnivorous species, careful attention must also be paid to growth efficiency, mortality rate and product quality.
- *Obtain a better understanding of the systems through more data collection.*
  It has been shown that assumptions made concerning energy demand from feed provision and on-site demand notably affects results. Also, vast differences are seen between farm sites. Many studies may also already be outdated due to technological development.
- *Pay attention to potential trade-offs.*
  Energy efficiencies are important, but also energy sources and potential trade-offs with other important aspects such as ecosystem impacts.
- *Improve knowledge capacity regarding extensive pond systems.*
  Pond design, paddle-wheel construction and better monitoring of oxygen levels are potential energy thieves. As these systems are important for the bulk of seafood produced from farming, optimising these systems will have big impact.
- *Improve knowledge capacity building between countries.*
  There are significant differences in energy efficiency between countries to produce the same species. As few countries dominate global production, simple targeted campaigns could have big impact on the whole sector. Business-to-business competition with e.g. patented feed formulas is however an obstacle. In less developed countries, old technology using large amounts of fossil fuel to produce low-quality feed is compromising energy efficiency of production, among other things, thus advocating for shifting to commercial feeds in these regions.
- *Set priorities on energy reduction versus use of different energy sources for effective policy instruments.*
  Some production systems may require more energy than others, but can operate with renewable energy. Others may be more dependent on fossil fuels, but make use of less energy.

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