

Energy Return on Investment for Aquaponics: Case Studies from Iceland and Spain

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Abstract Energy use in food production is linked to environmental impact, as most agricultural practices are reliant on fossil fuels. It is therefore of importance to locate food production methods that are less energy intensive than current methods and are also less polluting. Energy return on investment (EROI) is the ratio between the energy used to construct and maintain a given energy production system, against the energy that is provided by the system. Aquaponic systems have environmental benefits over conventional aquaculture systems as the waste is used within the

system as fertilizer for plants. In this paper, we analyse the operational performance of three aquaponic systems. Two systems were located in Iceland, and one in northern Spain. We also analyse the energy output with respect to edible protein contents. After 10 years of partially simulated operation, the EROI of the Hondarribia, Sudarvogur and Akur systems was 0.055:1, 0.016:1 and 0.106:1, respectively. Our results indicate that aquaponic operations benefit from operating within a greenhouse and that direct electricity consumption is the largest energy input in the aquaponics systems. The aquaponics systems studied returned one half to one tenth the EROI as compared to conventional fisheries or aquaculture.

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Introduction

Humans have moved away from being hunter-gatherers to food producers. We are no longer dependent to the same extent on external factors on what we can eat. This change in behaviour has, in recent decades, been driven by the use of fossil fuels where larger quantities of food are being produced in a relatively shorter timespan. In fact, the relation between human well-being in general and energy use has been demonstrated in quite some detail (Pimentel and Pimentel 2007; Lambert et al. 2014). It is known that the standard of living has been raised by the use of depletable fossil fuels (Pimentel and Pimentel 2007). However, as the global population grows, the need for food increases. For example, the production of fish is expected to increase by 19% from the period 2012–2014 to 2024 (OECD/FAO 2015). Most of this increase is expected to be a result of increased aquaculture production. The Food and Agriculture Organization of the United Nations (FAO) expects that aquaculture contributes 96 Mt to the global 191 Mt fish

production by 2024. According to the FAO, aquaculture production surpassed conventional fisheries in raw output for the first time between 2012 and 2014. Global consumption of fish per capita per year is also expected to increase from 19.7 kg in 2012 in to 21.5 kg in 2024. Future consumption of fish will inevitably depend heavily on aquaculture (OECD/FAO 2015). This reliance on aquaculture is closely connected to the increase in global fish consumption since the late 1990s. Figure 1 demonstrates that fish consumption has grown proportionally with global population until around 1995 where an increase in fish production is shown clearly.

To avoid over exploitation of the most common wild fish species, other methods need to be used for fish production. Aquaculture has been shown to be suitable for high output production but has various impact on the natural environment. This is especially the case for offshore aquaculture production where two-way interactions between the production system and the environment are numerous. Off-shore aquaculture systems modify the surrounding natural habitats, soil, water, landscape, and wildlife (Dosdat 2002). Aquaculture can not only help relieve pressure on fish stocks, but also put pressure on surrounding ecosystems. Fish is a desired product for its energy content, but moreover for its high protein content. As protein is a sought-after source, it is valuable to examine which production method provides the highest protein and energy yield. Such information should prove valuable for decision makers as it can serve as a guide to which production technology should be promoted and eventually used to supply protein and energy in food form to societies. It is the intention of this paper to shed light on the energy intensity of fish production using aquaponic technologies. To do this, the energy return on investment (EROI) methodology was used where three systems were analysed: two in Iceland and one in Spain. These locations were chosen because of good access to real data and operational experience. Two methods were used in this paper, the first estimates all energy as equal in inputs and outputs. We then use a method, perhaps more suitable to

EROI studies on food production, which estimates only the protein energy from the food product: the edible protein energy return on investment ($_{ep}$ EROI) (Hamilton et al. 2013). The EROI methodology is in line with the methodology used in Life Cycle Assessment (LCA), where LCA focuses on environmental impact of systems, while EROI focuses on energy efficiency. Similar data are gathered in EROI and LCA calculations, whereas subsequent computations differ. Similar studies were conducted by Vázquez-Rowe et al. (2014), Hamilton et al. (2013) and Pracha and Volk (2011), where the edible protein EROI ($_{ep}$ EROI) was demonstrated and calculated. The findings of this paper can assist policymakers when constructing policies regarding food production. This is of particular importance when multiple types of energy are available within a region. The paper can also serve producers of fish considering alternative production methods which may potentially be more energy efficient depending on location.

Aquaponics

The term aquaponics is used to describe combined systems of aquaculture and hydroponics. The method has received increased interest recently due to its potential for improvements with regard to sustainability (Thorarinsdottir et al. 2015; Goddek et al. 2015). Aquaculture is the practice of producing aquatic animals and plants, especially fish, in ponds, tanks or containers (Blidariu and Grozea 2011). Hydroponics are systems where plants are produced without the need for soil. Aquaponic systems attempt to solve the negative effects of aquaculture and hydroponics systems (Blidariu and Grozea 2011). Hydroponics also require expensive nutrients and flushing of the systems can lead to issues regarding waste disposal. Aquaculture systems need to be constantly cleaned, a process where nutrient-rich water is disposed of and replaced with fresh water. In aquaponic systems, nutrient-rich water from the aquaculture is deliberately used as nutrient for the hydroponic system. This not only eliminates the disposal problem of the aquaculture system but also eliminates the feedstock problem for the hydroponic system (Blidariu and Grozea 2011). This circular flow is shown in Fig. 2.

Ammonia, along with faeces, uneaten food etc., accumulate in aquaculture systems. Such accumulation is toxic for fish. Using a biofilter, the ammonia is oxidized to nitrite, and subsequently to nitrate. Ammonia and nitrite are toxic to fish in small concentration. Nitrate on the other hand can be tolerated in higher levels. The conversion from ammonia to nitrite and nitrate, respectively, is carried out by the bacteria *Nitrosomonas* species and *Nitrobacter* species. Having a nitrate-rich solution, a suitable fertilizer is available for plant production. The excess water from the hydroponic system has lower nitrate levels, therefore ready to be recirculated

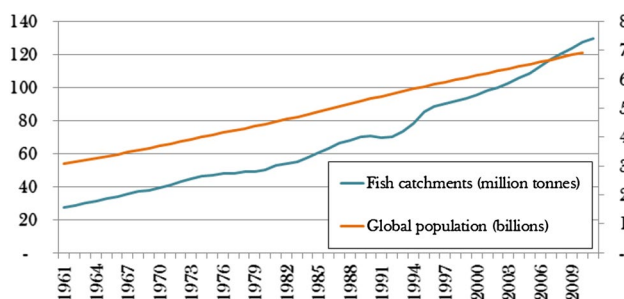


Fig. 1 Global fish catchments (y-axis on the left) and human population (y-axis on the right) (OECD 2015)

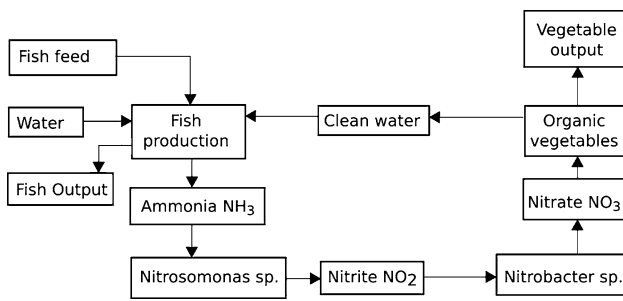


Fig. 2 Flow of materials in an aquaponic system. Figure partially adapted from Blidariu and Grozea (2011)

into the aquaculture system. Aquaponic systems are what is called recirculating aquaculture systems (RAS), where filters are used to clean the water for re-circulation. Various species have been grown in the Nordic countries using RAS technologies. Tilapia, as is grown in the systems under study, requires water temperatures of approximately 20°–30° C (Dalsgaard et al. 2013).

Materials and Methods

In this section, we outline the basic concepts used in our work, a detailed description of the systems we study and how calculations were conducted.

Energy Return on Investment

Energy return on investment (EROI) can be expressed as shown in Eq. 1 (Atlason and Unnthorsson 2013).

$$EROI = \frac{\text{Energy output from a system}}{\text{Energy used for constr. and operation}} \tag{1}$$

This equation can be further expressed as

$$EROI = \frac{\sum ED_{out}}{\sum ED_{in}} \tag{2}$$

where $\sum ED_{out}$ is the sum of energy produced and delivered within a boundary chosen. $\sum ED_{in}$ is the direct energy used to construct and operate a given system. The inputs are calculated as the direct energy used, such as electricity for daily operation of the system and also indirect energy for production of materials used by the system. When accounting for indirect inputs, the EROI equation is generally presented as

$$EROI = \frac{\sum ED_{out}}{\sum ED_{in} + \sum p_k m_k} \tag{3}$$

where p_k is a material used for construction and maintenance and m_k is the embedded energy content of those

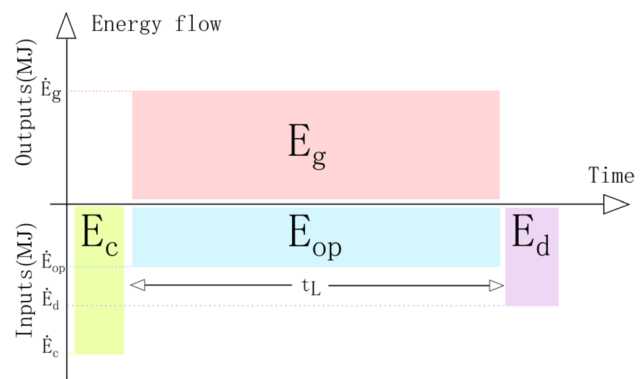


Fig. 3 Energy expenditures and production from a given system, adapted from Murphy et al. (2011) and Herendeen and Cleveland (2004)

materials. Output products can be calculated within different boundaries. These can be direct outputs, after the product has been processed or delivered to consumer. The boundaries were standardized in a study by Murphy et al. (2011). In this study, the boundaries used are $EROI_{std}$ which include direct and indirect input energy against the direct energy output. This is because of uncertainty with regard to downstream processes. Figure 3 shows, in a graphical manner, a system where output is energy. The project is initiated at time t as the system is constructed. Energy is then used at a constant rate over the construction time, denoted as t_c . The construction phase used a total energy of E_c . The total flow of energy for the construction phase can be shown to be (Murphy et al. 2011)

$$\dot{E}_c = \frac{E_c}{t_c} \tag{4}$$

As the construction phase has been completed, a constant flow, or a predictable flow, of output energy is expected at rate \dot{E}_g over the lifetime t_L . The energy flow, \dot{E}_{op} is used for operation and maintenance. Energy is also used in the decommission of the project, expressed as E_d . The net energy output from a given system can be shown as

$$E_{net} = E_g - E_{op} - E_c - E_d \tag{5}$$

whereas the EROI for the system at a given time is shown as (Murphy et al. 2011)

$$EROI = \frac{E_g}{E_c + E_{op} + E_d} \tag{6}$$

The sum of energy expenditures shown in Fig. 3, namely E_{op} , E_c and E_d contribute to the denominator in Eq. 3. In this study, indirect energy for construction materials of the setup is accounted for, the direct input energy and direct energy outputs. Indirect energy information was gathered

from the inventory of carbon and energy (ICE) published by the sustainable energy research team at the University of Bath (Hammond and Jones 2008). Energy contents of various food products was gathered through the nutrient value database provided by the U.S. Department of Agriculture (USDA 2015). To estimate the calorific value of the feed, information was gathered from several sources. First, information from the producer of the feed in use in the systems was studied. Then, three studies outlining energy content of fish feed were used as a complementary material (Cuzon 1985; Einen and Roem 1997; Refstie et al. 1998). To calculate the edible protein energy return on investment of the different tilapia systems, only the energy content of the protein content is evaluated as an output. Of raw tilapia, 20% is assumed to be protein (USDA 2015). The protein is also estimated to contain 16.73 MJ/kg (WHO 1991). The equation to calculate the edible protein energy return on investment (${}_{ep}EROI$) is therefore as follows:

$${}_{ep}EROI = \frac{\sum T_{mass} * P_{cont} * 16.73}{\sum ED_{in} + \sum p_k m_k}, \quad (7)$$

where $\sum T_{mass}$ is the total mass of tilapia output from a given system and P_{cont} is the protein content of a given fish species, raw.

Characterization of the Studied Systems

In this section, the three aquaponic systems used for the EROI calculations are briefly described. Two small systems are located in Iceland, while a larger system is located in Hondarribia, Spain.

Hondarribia System

The aquaponic system located in Hondarribia was designed and constructed by Breen aquaponic technologies, Spain. The system produces on average 2 t of tilapia, 230 kg of lettuce, 250 kg of tomatoes, 2 kg basil, 3

kg parsley, 20 kg chili pepper and 10 kg of peppers annually. Also, 875 kg of vermicompost is produced. The system manages to keep its waste to a bare minimum, where the total mass of sludge is converted into compost. Energy for heating the system is excluded, as it manages to use waste heat from a co-generation system.

No synthetic fertilizers are used within the Hondarribia system. Fresh water is gathered using rain water. On average, 10% of the water within the system is renewed weekly. This results in approximately 9 m³ of new water every month. Table 1 demonstrates the mass of materials used in the Hondarribia system. Figure 4 shows the system constructed in Hondarribia. Figure 5 depicts schematically how the system operates. One can see that water outputs from the tilapia are fed into a tank of Australian lobster culture. The lobster consumes uneaten food from the tilapia, delivering cleaner water. The lobster serves more as a water filter than a food source. The lobster is in small quantities and is not calculated as an output from the system. The Hondarribia system is located in a greenhouse, allowing for the natural environment to provide lighting and heating.

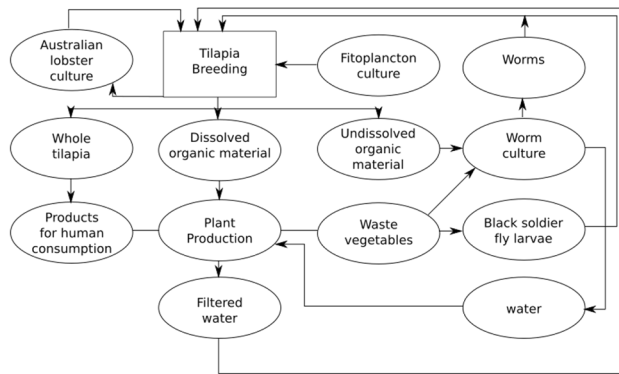


Fig. 5 A schematic description of the Hondarribia system

Fig. 4 The aquaponic system installed in Hondarribia by Breen aquaponic systems



Akur System

At Akur, Iceland, approximately 600 kg of tilapia is produced annually, 130 kg of tomatoes and 15 kg of okra. The system consists of three 4 m³ tanks. From each tank, water is diverted into a 110 mm collection pipe. The water then passes through a drum which removes solid particles. After the water is filtered, it enters a collection tank and a biofilter for nitrification. From there, it is pumped towards three destinations: one pipe goes to the fish tanks, one pipe to the biofilter and finally one pipe goes towards the hydroponics system. The biofilter is a 1000 l Intermediate bulk container (IBC) tank, containing approximately 0.4 m³ of surface medium. An air pump keeps the surface medium on constant movement within the biofilter. The aquaponic system at Akur is shown in Fig. 6.

Nitrification takes place within the biofilter as previously explained. The pipe leading from collection tank towards the hydroponics system is then divided for different beds where plants are located. After passing through the hydroponics system, the water then flows back into the collection tank. The water in this system is passive where gravity is used to allow for it to flow the desired way. The fish are fed daily using automatic feeders. The fish are fed 1% of its body mass daily. At the Akur system, it is assumed that lighting is provided artificially using 220 W/m² within the 50 m² area where the hydroponics system is located. It is furthermore assumed that lights are turned on during eight months of the year, 16 h per day. This had to be assumed as no real data was available since the lighting is controlled automatically and not logged. The other months are the summer months, with long days in the northern hemisphere and the need for artificial lighting is negligible.



Fig. 6 The aquaponics at Akur

Sudavogur System

The system located in Sudavogur, Iceland, is estimated to produce roughly 115 kg of tilapia and 60 kg of lettuce per year. The system consists of 1 m³ fish tank, 1 m³ separation tank and biofilter that consists of two 0.2 m³ barrels. Six 0.3 m³ plant beds and a 0.5 m³ sump tank are also on site. Water is pumped from the sump tank into the fish tank. From the fish tank, water flows into the separation tank where solid particles are separated from the water. After leaving the separation tank, the water goes through the biofilter where conversion from ammonia to nitrate takes place. The filter uses a surface medium to assist with filtration. From the biofilter, the water then flows to the plant beds. In each plant bed, approximately 40 plants float in expanded polystyrene trays using electric lighting for 16 hours a day. From the plant beds, the water again flows to the water tank. The Sudavogur system is located within an industrial complex in Reykjavik as is shown in 7.

EROI Calculations

The boundary chosen within the EROI framework for this study is EROI_{std}. All direct and indirect energy is accounted for, along with the direct output before processing (Fig. 7). The embodied energy in all materials used for constructing the systems is accounted for. Materials were weighed allowing for the use of real data. The real output from an entire year was used in the calculations from Hondarribia. From the Icelandic system in Sudavogur, data were available from two production runs, providing a stronger insight into the operations. In total, the time period comprises 138 days. Within the two production runs, fish and vegetables were harvested twice. The data from these runs are then used to simulate a 10-year production run. For the system in Akur, a two-month production run, where harvesting was included, was used as a basis for



Fig. 7 The Sudavogur system is located within an industrial complex

the calculations. To see the development of the systems in time, it was assumed that the systems would operate for 10 years without any major maintenance or incidents, keeping a constant output from their base year. It was assumed that electricity and feed consumption would also be kept constant. Heating for all systems is excluded for different reasons in every case. The Hondarribia system uses waste heat from generators for heating. The use of this waste heat is excluded in this study. Also, the Akur and Sudavogur systems use hot water from the abundant renewable geothermal resources in their vicinity for heating. Geothermal resources are in this study assumed to be a public good as they are non-rivalrous, especially in Iceland (Simon 2007). However, if energy used for heating would be included, the EROI results would likely decline to some extent. Public or common goods such as sunlight or wind energy are generally not included in EROI calculations and will therefore be excluded in this study. As the protein content is of high importance, the edible protein energy return on investment is calculated. This method assumes that the output is only the energy content of the protein. The protein energy content is assumed to be 16.73 MJ/kg for tilapia (Tyedmers 2004; WHO 1991).

Results

The total input energy used for the system in Hondarribia was 230,234 MJ. Of that, the system used 22,400 kWh (80,640 MJ) of electricity annually. The output from the system was 8380 MJ and is assumed to be kept constant. The majority of output energy was in the form of tilapia, or 8034 MJ. After one year of operation, the system has an EROI of 0.036:1. As the original investment energy is only consumed in the beginning of the lifetime, the EROI improves as the system operates for longer. It is assumed that only electricity and feed are needed for the operation of the plant. The EROI of the Hondarribia system therefore reached 0.055:1 10 years in the future, approaching its plateau of diminishing returns. It can be seen that the limit for the Hondarribia system is around 0.06:1. This development is shown in Fig. 8 and Table 2.

The distribution of inputs for the Hondarribia system is shown in Fig. 9. One can see that electricity consumption contributes the most to the inputs, followed by the feed and PVC pipes. After operating for 10 years, the electricity consumption grows even further.

EROI for the Sudarvogur system after one year of operation was 0.012:1. After operating for 10 years, the system reached an EROI of 0.016:1. The development of the Sudarvogur system can be compared to the Hondarribia system in Fig. 8. This difference in EROI results can be linked to the relatively high use of electricity in the

Sudarvogur system, where 8427 kWh were used over a period of one year. This is a quarter of the usage by the Hondarribia system, even though the Sudarvogur system is much smaller when looking at energy outputs. The reason for this is the location of the systems. The Hondarribia system is located within a greenhouse in northern Spain, where relatively little additional lighting is required and sunlight is abundant for the plants. The Sudarvogur system is located inside an industrial complex where lighting mostly needs to be provided for, hence the heavy usage of electricity. The relatively heavy usage of electricity is further visualized in Fig. 10.

The Akur system is located within a greenhouse. It is less reliant on artificial lighting than the Sudarvogur system. Electricity consumption at the Akur system was 9267 kWh, followed by the construction of the system, in particular the use of wood used to construct plant beds (499 kg). The output from the system over the first year was calculated to be 3678.4 MJ and is considered to be kept constant for the continuous operation. A dissemination of the energy used in the construction of the Akur system is shown in Fig. 11. The EROI from the Akur system was 0.085 after the first year of operation. After 10 years of operation, the system has returned an EROI of 0.106:1. The results from Akur are considerably better than the other Icelandic system located in Sudarvogur and more than two-fold improvement when compared to the Hondarribia system.

When looking at the increase of energy in biomass of tilapia within the systems, one can see that the increase is 8,034 MJ in the Hondarribia system, 136 MJ in the Sudarvogur system and 177 MJ in the Akur system. Comparing the input energy to the net energy increase of tilapia, it is evident that the Hondarribia system outperforms the Icelandic systems. For each MJ of increased tilapia biomass, the Hondarribia system used 29 MJ, the Akur system 178 MJ and the Sudarvogur system 308 MJ. This can be directly related to the fact that the Hondarribia system is the only system growing fish from the very early stage, and the Sudarvogur system is heavily reliant on artificial lighting.

Edible Protein Energy Return on Investment

The intention of producing fish is not to create net energy for society, but rather high protein output. We are therefore asking the question, “how much protein will this amount of energy provide?”. In this case, $epEROI$ is perhaps a more suitable indicator when looking at food production. When assuming that the output protein of the tilapia is the main output, we found the EROI to be lower. After 1 year of operation, the Akur, Hondarribia and Sudavogur systems have an $epEROI$ of 0.043:1, 0.029:1 and 0.009:1

respectively. Also, after 10 years of operation, the systems have an $epEROI$ of 0.059:1, 0.045:1 and 0.012:1. The $epEROI$ development is shown in Fig. 12.

In these calculations, the input energy is the same as in previous calculations, but only the output energy is calculated using equation 7. The development for edible protein energy return on investment is shown in Table 3.

Relation to Previous $epEROI$ Results

The EROI methodology has previously been used to study fish production; for example, salmon farming has been shown to return approximately 0.15:1 unit of edible protein energy for each unit used in the production process, compared to values of 0.012:1 to 0.056:1 in this study (Folke 1988; Tyedmers 2004). From industrial fisheries, the EROI is quite dependent on the equipment used in the process. Herring, caught using purse seine, has been shown to have an EROI of 0.56:1, which is some of the highest ratios reported. Other industrially harvested species have shown to have lower returns. Cod for example, caught in the North Atlantic, returns around 0.1 unit for every unit used in the harvesting process. Tuna, caught using longline, has an EROI of 0.022:1 (Tyedmers 2004). The average EROI for European fishing fleets is approximately 0.11:1 (Guillen et al. 2016). Data from Icelandic fisheries was presented in a previous study by Tyedmers (2001). The year sampled was 1997 using data from 1443 vessels. The lowest EROI from Icelandic fisheries was from vessels using gillnet, generally landing cod, plaice, haddock and redfish, resulting in an EROI of 0.029:1 (Tyedmers 2001). The highest EROI from Icelandic fisheries was shown to be from trawlers catching cod, haddock, redfish and saithe. Those trawlers returned an EROI of 0.093:1. These values are representative for Northern Atlantic fisheries from Canada, Norway, Iceland and Germany, who all received similar EROI values (Tyedmers 2001). In contrast to many EROI studies, only the edible parts of the fish and vegetables are calculated as an output. Even though other parts of the fish may be rich in energy and suitable as feed or any other co-product. It is, however, considered that the waste will not be contributed to society, hence it is excluded. Tilapia from an Israeli aquaculture system has been shown to have an EROI 0.066:1 (Tyedmers 2004). Also, tilapia farmed in a Zimbabwe pond system was shown to have an EROI of 0.06:1. Tilapia farmed in an intensive cage culture in Zimbabwe has an EROI of 0.025:1 (Tyedmers 2004). Table 4 illustrates some of the major findings from previous studies and places the findings from this study in context. Table 4 demonstrates that the aquaponics systems in this study scored relatively low compared to other fish production systems when looking at $epEROI$.

Until now, the literature has lacked any information about the EROI of aquaponic production. Previous EROI studies for farmed tilapia provide a comparison to the tilapia farmed in the aquaponic systems presented in this study. As shown in Table 4, aquaponics systems have a relatively low $epEROI$. What is, however, not demonstrated in this study is the fuel intensity of such production. The electricity consumed in Iceland comes from a renewable source, either geothermal or hydro while offshore ships conducting trawling for example need diesel oil.

It can be concluded, by looking at the comparison shown in this section, that aquaponics systems have a considerably lower $epEROI$ values than many other fish harvesting methods.

Discussion

As we demonstrate, the Hondarribia data did not include the input of juvenile fish. This is because the energy content of the juveniles is of very little significance and will not have any effects on the EROI results. We also found that the low EROI provided by the Sudarvogur system is directly related to the heavy reliance on electricity for artificial lighting. It is, however, questionable if electricity consumption in Spain and Iceland can be compared joule by joule as most, if not all, electricity consumed within the capital area in Iceland is produced using either hydropower or geothermal energy. All forms of energy are not equal, because of differences in usability, price and other factors. The difference in usability is often referred to as energy quality. Methods are, however, available to adjust for energy quality. Even though quality correction is attempted in this study, quality correction for food is a field within the EROI literature that has to be cleared to some extent as bio fuels often require the same inputs as food. This is partially addressed in this study by comparing the systems based on protein output. When looking at Table 4, it is evident that the EROI values from this study are very low compared to other forms of fish harvesting. The studies presented in Table 4 are not adjusted for energy quality. This may skew the results as the input energy (heat and electricity) in the study presented are mostly from geothermal and hydro (renewable sources), while most other methods rely on fossil fuels in their harvesting procedures. It is notable that the Akur system outperformed the Hondarribia system as it seems that the Hondarribia system produces more fish compared to the electricity used. At Akur 0.07, MJ of tilapia is returned for each MJ of electricity consumed. At the Hondarribia system, 0.1 MJ is returned. Table 1 shows that the input fish to the Akur system has already grown to some extent and does not go through the whole growth curve while located at Akur. The Hondarribia system may

Table 1 Input and output energies from the examined aquaponic systems

Product	MJ/kg	Hondarribia		Sudarvogur		Akur	
		Amount (kg)	Total (MJ)	Amount (kg)	Total (MJ)	Amount (kg)	Total (MJ)
Input energies							
PVC Pipes	67	738	49,446	6.19	415	8.6	576.2
PP Pipes	84.4	80	6752	32.25	2722	1.6	135.04
Fibreglass cont.	28	15	420	–	–	144	1344
Expanded clay	3	1120	3360	–	–	–	–
Steel	20.1	100	2.010	–	–	–	–
Steel tubes	19.8	–	–	8.12	161	8.1	160.8
PE Film	89.3	50	4465	–	–	–	–
Wood	7.11	234	1663	193	1372	499	3548
Plywood	15	–	–	277	4155	–	–
Copper	42	1	42	–	–	–	–
PC	112.9	23	2596	–	–	–	–
PU sheet	86.4	–	–	17.2	1486	16.2	1399
Expanded PS	88.6	–	–	2.5	222	–	–
PE	85.83	216	18,539	–	–	–	–
Electricity		22,400 kWh	80,640	8427 kWh	30,339	9267 kWh	33,360
Plant seed	1.8	–	–	0.96	1.7	–	–
Small fish	4.017	–	–	80	321.3	554.4	2227
Feed	20.1	3000	60,300	43.8	880.38	66.5	1337.5
Total	–	–	230,234	–	42,073	–	44,088
Output energies							
Tilapia	4.017	2000	8034	114	458	598.7	2405
Lettuce	0.58	230	133	101	34.22	–	–
Tomatoes	0.66	250	165	–	–	130.1	1030.6
Basil	0.96	2	1.9	–	–	–	–
Okra	1.38	–	–	–	–	14.7	243
Parsley	1.5	3	4.5	–	–	–	–
Chili pepper	1.67	20	33.4	–	–	–	–
Pepper	0.83	10	8.3	–	–	–	–
Total	–	2515	8380	173	492	743.5	3678.4

Note that 1 kWh = 3.6 MJ

Table 2 EROI results for the first 10 years of operation from the systems under study

Year	Hondarribia	Sudarvogur*	Akur
1	0.036:1	0.012:1	0.078:1
2	0.045:1	0.014:1	0.091:1
3	0.049:1	0.015:1	0.097:1
4	0.051:1	0.016:1	0.100:1
5	0.052:1	0.016:1	0.102:1
6	0.053:1	0.016:1	0.103:1
7	0.054:1	0.016:1	0.104:1
8	0.055:1	0.016:1	0.105:1
9	0.055:1	0.016:1	0.105:1
10	0.055:1	0.016:1	0.106:1

The Sudarvogur system includes two production runs

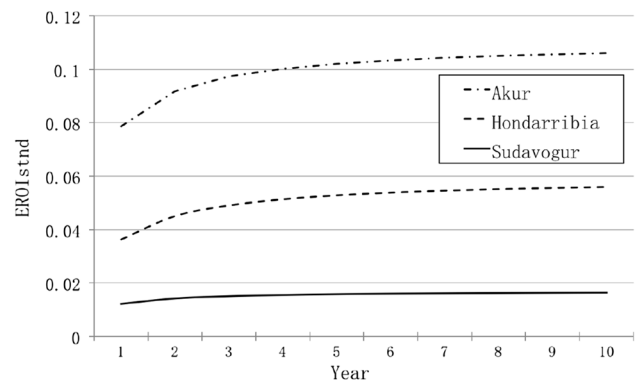


Fig. 8 EROI developments of the systems under study

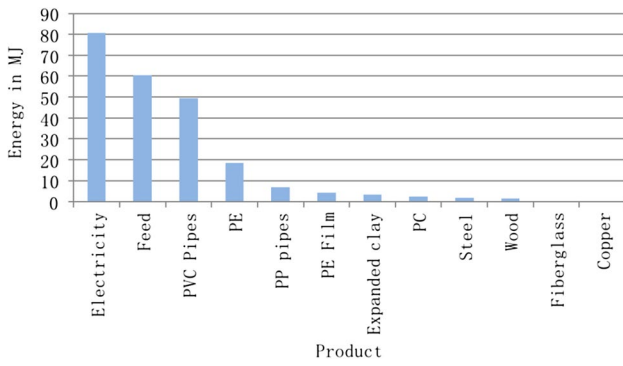


Fig. 9 Inputs to the Hondarribia system for the first year measured in MJ. Y-axis values are shown in thousands

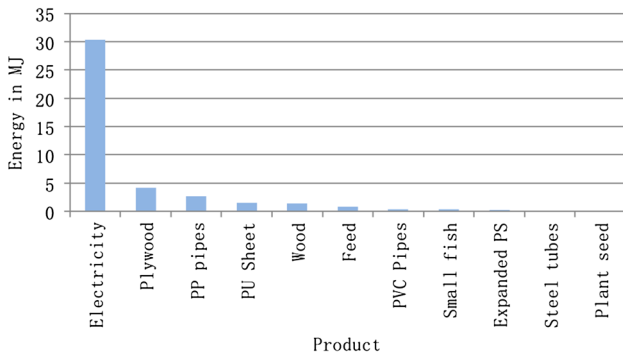


Fig. 10 Inputs to the Sudarvogur system for the first year measured in MJ. Y-axis is shown in thousands

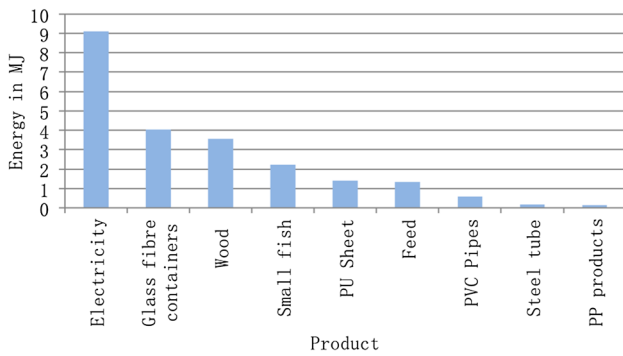


Fig. 11 Inputs to the Akur system for the first year measured in MJ. Y-axis values are shown in thousands

therefore provide a more holistic result as it depicts the production system from the juvenile stage of the tilapia throughout its life within the system. Overall, the Icelandic systems can be effectively compared to each other. The comparison to the Hondarribia system is questionable, but the results from that particular system contribute to the EROI literature on a standalone basis. To attempt a comparison, the energy use per tilapia biomass increase was

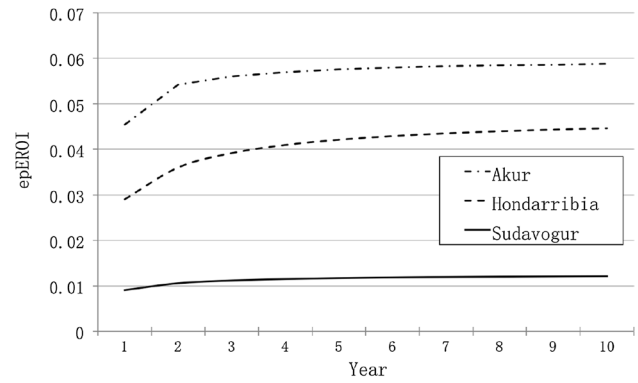


Fig. 12 The development of $epEROI$ for the systems under study

Table 3 EROI results for the first 10 years of operation from the systems under study when looking at the edible protein energy return on investment, $epEROI$

Year	Hondarribia	Sudarvogur	Akur
1	0.029:1	0.009:1	0.045:1
2	0.036:1	0.011:1	0.054:1
3	0.039:1	0.011:1	0.056:1
4	0.041:1	0.011:1	0.056:1
5	0.042:1	0.012:1	0.057:1
6	0.043:1	0.012:1	0.057:1
7	0.044:1	0.012:1	0.058:1
8	0.044:1	0.012:1	0.058:1
9	0.044:1	0.012:1	0.059:1
10	0.045:1	0.012:1	0.059:1

calculated. By doing so, one can see that the Hondarribia system outperformed the Icelandic systems as it required less energy input for every fish output gained. The difference in energy use for each MJ of tilapia output is shown in Fig. 13.

The relatively favourable results of the Akur system can also be contributed to its favourable geological location. The location of both Icelandic systems allow for an easy access to a renewable heat source, excluding any need for heating to be conducted using fossil fuels or other means of non-renewable energy sources. Using non-renewable energy sources, which can not be considered as a public good, would inevitably lead to inclusion in the calculations and result in a much lower EROI. We also found that the Icelandic systems are delivering much less tilapia output per energy input; this is because the systems are still in the development phase and have great potential for improvement. In relation to the previous aquaculture-specific studies, we found that the Hondarribia system returned similar results to the Israeli aquaculture farm and also similar results to those of the Zimbabwe pond system. The Akur

Table 4 Comparison of ep EROI values from this study with other findings

Country	Year	Gear type	Top four species landed (by weight)	Edible protein return	Reference
Canada	1999	Mobile-seine	Cod	0.25:1	Tyedmers (2001)
Norway	1998	n/a	Herring-Cod-Saithe-Ling	0.22:1	Tyedmers (2001)
Norway	1998	Mobile-seine	Herring-Cod-Saithe-Haddock	0.17:1	Tyedmers (2001)
Sweden	1988	Ranching w/o offshore fishery	Salmon	0.14:1	Folke (1988)
Canada	1999	Trawl	Redfish-Flatfish-Cod-Gr.Halibut	0.13:1	Tyedmers (2001)
Norway	1998	Longline	Cod-Ling-Tusk-Catfishes	0.13:1	Tyedmers (2001)
Sweden	1988	Cages	Salmon	0.13:1	Folke (1988)
Canada	1999	Mobile-seine	Plaice-Witch-Cod-	0.12:1	Tyedmers (2001)
Norway	1998	n/a	Cod-Saithe-Herring-Ling	0.12:1	Tyedmers (2001)
Canada	1999	Trawl	Silver-hake-Haddock-Saithe-Cod	0.11:1	Tyedmers (2001)
Norway	1998	GN-HL	Cod-Herring-Saithe-Haddock	0.11:1	Tyedmers (2001)
Norway	1998	Trawl	Saithe-Cod-Herring-Haddock	0.11:1	Tyedmers (2001)
Germany	1998	Trawl	Redfish-BIWhiting-Herring-Capelin	0.11:1	Tyedmers (2001)
Norway	1998	Mobile-seine	Cod-Herring-Haddock-Saithe	0.099:1	Tyedmers (2001)
Canada	1999	Longline	Cod-Haddock-White-hake-Tusk	0.093:1	Tyedmers (2001)
Iceland	1997	Gillnet	Cod-Saithe-Haddock-Porbeagle	0.093:1	Tyedmers (2001)
Iceland	1997	Trawl	Redfish	0.093:1	Tyedmers (2001)
Iceland	1997	Trawl	Cod-Haddock-Saithe-Redfish	0.092:1	Tyedmers (2001)
Iceland	1997	Trawl	Cod-Redfish-Saithe-Haddock	0.092:1	Tyedmers (2001)
Norway	1998	Trawl	Cod-Saithe-Haddock-Shrimp	0.088:1	Tyedmers (2001)
Iceland	1997	Mobile-seine	Cod-Dab-Plaice-Haddock	0.086:1	Tyedmers (2001)
Norway	1998	n/a	Cod-Herring-Saithe-Mackerel	0.085:1	Tyedmers (2001)
Iceland	1997	Longline	Cod-Haddock-Catfish-Tusk	0.084:1	Tyedmers (2001)
Norway	1998	Longline	Cod-Haddock-Herring-Gr.Halibut	0.079:1	Tyedmers (2001)
Iceland	1997	Handline	Cod-Saithe-Redfish-Haddock	0.078:1	Tyedmers (2001)
Iceland	1997	Longline	Cod-Catfish-Haddock-Tusk	0.071:1	Tyedmers (2001)
Norway	1998	Trawl	Cod-Saithe-Redfish-Haddock	0.07:1	Tyedmers (2001)
Iceland	1997	Handline	Cod-Saithe-Catfish-Redfish	0.069:1	Tyedmers (2001)
Israel	1993	Aquaculture	Tilapia	0.066:1	Ackefors et al. (1994)
Germany	1998	Trawl	Cod-Saithe-Sprat-Flounder	0.06:1	Tyedmers (2001)
Zimbabwe	1996	Semi-intensive pond culture	Tilapia	0.06:1	Berg et al. (1996)
Iceland	2016	Aquaponics (greenhouse)	Tilapia	0.056:1	This study
Spain	2016	Aquaponics (greenhouse)	Tilapia	0.045:1	This study
Sweden	1988	Ranching with offshore fishery	Salmon	0.04:1	Folke (1988)
Canada	1999	Gillnet	Cod-Saithe-Gr.-Halibut-White-hake	0.031	Tyedmers (2001)
Iceland	1997	Gillnet	Cod-Plaice-Haddock-Redfish	0.029	Tyedmers (2001)
Zimbabwe	1996	Aquaculture	Tilapia	0.025	Berg et al. (1996)
Germany	1998	Trawl	Plaice-Sole-Cod	0.018	Tyedmers (2001)
Germany	1998	Trawl	Cod-Plaice-Haddock-Sole	0.016	Tyedmers (2001)
Iceland	2016	Aquaponics (industrial complex)	Tilapia	0.012	This study

Findings are listed in an order of EROI values, highest first

farm provided more favourable results than the Israeli or Zimbabwe farms. In fact, the Akur system returned similar results to Icelandic trawlers catching cod, haddock, redfish and saithe (Guillen et al. 2016). The production at the Akur system provided considerably less EROI compared to salmon farming. The Sudarvogur system performed much

worse with respect to EROI than any other aquaculture farms with published EROI results. Even the lowest performing Icelandic gillnet vessels provided three times more favourable EROI than that of the Sudavogur system (Guillen et al. 2016). It is then a strong indicator that aquaponic systems, when located inside industrial complexes are

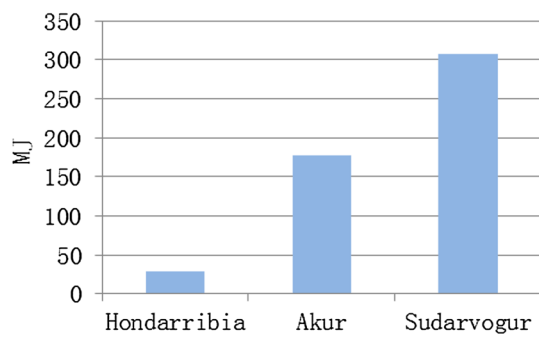


Fig. 13 Amount of energy (MJ) used per MJ of net tilapia output

likely to provide very low EROI because of their intensive use of electricity. When comparing the energy efficiency in animal food production, be it for fish, beef or other types to vegetable production, it is evident that meat production is more energy intensive, regardless how it is viewed. This difference has been demonstrated through numerous studies (Liu and Gu 2016; Atlason et al. 2015b; Markussen and Østergård 2013; Pimentel and Pimentel 2007). One way to explain this difference in EROI between meat and vegetable production is by comparing the production processes. Meat production process is generally more complicated and involves an extra step, where vegetables or grain are not the direct output from the process, but are used as animal feed, where energy is lost. All systems analysed in this study are relatively small, where the largest produces merely 2 tons of Tilapia per year. It is therefore of interest to see if economies of scale would have an effect that could improve EROI results. Future research could include the expansion of the EROI analysis with regard to the Icelandic systems where the whole growth curve of the tilapia is included. Also, expanding the research and including different plants within the system could provide interesting results. Growing high-energy products such as sugar cane may provide more favourable EROI results. Therefore, optimizing the system with regard to EROI, where high-energy content fish in harmony with high-energy plants would shed a light on the potential of aquaponic systems and their potential to provide energy to society in a less polluting manner than conventional systems providing the same product. This would further shed a light on the $EROI_{ide}$ of aquaponics, i.e. the maximum EROI possible for a given system and the room for improvements (Atlason and Unnthorsson 2014).

Conclusion

The future of food production is a topic that is multifaceted. How societies will produce food with available energy is of vital importance and needs to be explored in order for

informed decisions to be made. In this study, it was shown that fish production using aquaponic systems has the potential to provide as much net energy to society as conventional fish breeding using aquaculture techniques. Aquaponic systems are, however, sensitive to inputs of public goods, such as geothermal or solar energy. Placements of aquaponic production systems has therefore potential for superior net energy performance but is heavily dependent on favourable geographic location. When looking at the edible protein energy return on investment, we found that $epEROI$ results from the aquaponics systems studied in this paper are considerably lower than other fish harvesting systems. This study indicates that when using fossil fuels, other fish harvesting techniques seem to be more appealing. The aquaponics systems do, however, offer the possibility to be placed where renewable energy can be utilized. However, studies with longer time frame of real data need to be conducted to provide deeper insights into large-scale potentials of such production.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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