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Integration of renewable energy sources into the aquaculture systems considering environmental and economic aspects

Marija Koričan[1], Maja Perčić[1], Nikola Vladimir *[1], Vladimir Soldo[1]

1 University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10002 Zagreb, Croatia

* Corresponding Author, e-mail address: nikola.vladimir@fsb.hr

ABSTRACT

Reductions of environmental footprint and lifetime costs are nowadays key aspects of most of human activities. Such concerns are also present in the aquaculture sector which involves the cultivation of aquatic organisms as well as all activities related to their processing, seeking to ensure sustainable growth. This paper deals with the environmental and economic aspects of aquaculture systems (involving aquaculture farms and relevant farm vessels) with a high share of renewable energy sources (RES). The energy needs of a typical aquaculture system are identified and Life Cycle Assessments (LCAs) of different power system configurations are performed. These configurations are also compared from the economical viewpoint, by the Life Cycle Cost Assessment (LCCA). Electrification of farm vessels is recognized as a key solution to reduce both the environmental footprint and operating costs. However, as shown by LCA, due to specific operating profile of farm vessels their energy needs can not be completely covered by RES, since an amount of electricity supplied from the national grid is needed. Therefore, the share of renewables will be dependent on the percentage of RES in the energy mix of the specific location of the aquaculture system. The LCCA analysis has shown that this form of integration requires larger investment which, if an unfavourable form of RES is chosen, may cause financial losses.

Keywords: renewable energy sources (RES); aquaculture; carbon footprint; LCA; LCCA

NOMENCLATURE

Abbreviations	
CF	Carbon Footprint
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
IEA	International Energy Agency
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Assessment
PTW	Pump-to-Wake
PV	Photovoltaic
RES	Renewable Energy Source
WTP	Well-to-Pump
Symbols	
A	Area (m^2)
BC	Battery capacity (kWh)
E_{rad}	Solar irradiation (MJ/m^2)
EC	Energy consumption (kWh/km)
EF	Emission factor (kg emission/kg fuel)
FC	Fuel consumption (kg/km)
P	Power (kW)
SFC	Specific fuel consumption
t	daily sun hours (h)

1. INTRODUCTION

Aquaculture involves the cultivation of aquatic organisms, including fish, shellfish, crustaceans and macrophytes. Due to the growth of population and thus food demand, there is rapid development in the aquaculture sector. According to the Food and Agriculture Organization (FAO), by 2018, world aquaculture production was 82.1 million tonnes, with an additional fishing catch of 96.4 million tonnes [1]. However, due to overfishing, ecosystems are endangered. Today, the required level of control is accomplished by using different types of sensors for measuring environmental parameters and remote monitoring to reduce food consumption and monitor the development of cultivated organisms. By implementation of automated feeders, sensors, monitoring systems, cranes and other equipment on barges, the autonomy of the aquaculture farms increases and allows them to be located away from the shore. Also, this reduces the load on the workboats thereby reducing their energy consumption. The drawback of this type of modernization is an increase in investment and operating costs [2].

According to the International Energy Agency, there has been an increase in CO_2 emissions worldwide over the years. With the enactment of the legislation (Kyoto Protocol), CO_2 emissions were limited and a continuous decline was recorded [3]. Although international shipping generates a small percentage of the Global Greenhouse Gases (GHGs) compared to land transport, there is a risk of an increase in these emissions of 50% - 250% by 2050 if no actions taken. Due to possible risks, several agreements have been reached that seek to influence environmental change in the world. To achieve environmental friendly power systems, renewable energy sources (RES) are being implemented [3]. Implementation of RES depends on the geographical characteristics and conditions in which it will be applied. According to the relevant literature, the example of Cyprus shows the influence of the Siberian anticyclone and the Indian monsoons, but also the influence of mountain peaks [2]. Interesting data were presented in [4] where a study of the dependence of solar potential on location was conducted. Croatian researchers [5] cite „jugo“ and „bora“ as the most significant forms of wind that can affect the annual amount of energy produced in Croatia. RES technologies are still under development and require further research.

In this paper, the focus is on the integration of solar energy in the aquaculture sector. According to IEA, the production of solar PV energy has a sharp increase and has the second-largest overall growth of all RES. Further development seeks to achieve an average annual increase of 15% [3]. Photovoltaic (PV) systems are characterized by high efficiency and CO_2 saving. The main problem of PV technology is the lack of space suitable for implementations. The application of PV technology in aquaculture farms could solve this problem by installing the system on the water surface and at the same time eliminate the use of water during maintenance (aquavoltaics) [7]. If the energy required in aquaculture farms can be produced through solar technology, it is possible to move the farm away from the mainland and thus increase aquaculture production [7]. This paper deals with the integration of renewables in the aquaculture systems, where a Norwegian aquaculture farm is taken as a test case. Although the Norwegian electricity grid has a large portion of hydropower [3], most aquaculture farms still use fossil fuels. According to Syse [10], 50% of the Norwegian fish farms use diesel generators to produce electricity while the rest is connected to the grid. Many studies deal with the problem of integrating RES into the ships. However, to the best authors knowledge, there are no publicly available studies that include LCA and LCCA analysis for the entire aquaculture system. This paper analyses the entire system, from aquaculture cages to required vessels. A fully-electric workboat is investigated and the efficiency of a PV system in an aquaculture farm is analysed. By performing LCA and LCCA analyses, the ecological and economic performance of the power system in an aquaculture farm is evaluated.

2. METHODOLOGY

Although aquaculture farms do not emit high levels of GHGs, according to the United Nations, all production sectors should proportionally contribute to the overall reduction of GHGs [8]. If we also consider the risk of a possible increase in emissions mentioned earlier, the importance of reducing GHGs emissions in each sector is obvious. The shipping sector is being pushed to reduce its Carbon Footprint (CF) which represents a relative measure of the total amount of CO_2 or $CO_{2\text{-eq}}$ emissions caused by indirect or direct activity or is accumulated over the life cycle of a product [8]. To help the estimate if the integration of RES is environmentally friendly and economically viable, a Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) were performed and the results were compared with a diesel-powered system. Given that Norway receives a large share of its electricity from RES and has a highly developed aquaculture sector, it was selected as the site for the implementation. The structure of the Norwegian electricity mix is shown in Figure 1, where the main source is hydroelectric power.

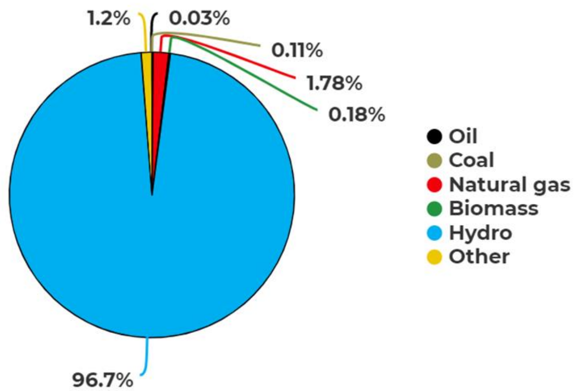

Figure 1 The Norwegian electricity mix in 2018

2.1 Energy demands of an aquaculture farm

Aquaculture system in a marine environment consists of cages, farm vessels needed for work or maintenance and onshore energy network, shown in Figure 2. The basic construction has no energy consumption but adding a feed barge with the installation of lighting, monitoring systems and other equipment, the energy consumption of the overall aquaculture system increases. Conventional vessels are powered by a diesel engine which emits high levels of CO_2 as well as other gases. In accordance with legal regulations, CO_2 emissions are striving to reduce, which is why the electrification of the fleet is carried out. Relocating the feeders and other equipment from the vessel to the barge, the energy demands of the vessel decrease, enabling to power it almost completely from RES.

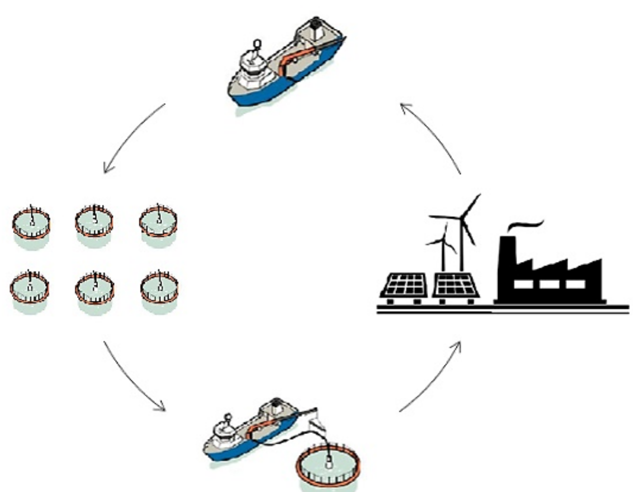

Figure 2 Simplified work process in an aquaculture farm

2.2. Integration of solar technology

Integration of solar technology into aquaculture entails several conditions. Since the efficiency highly depends on the dimensions of the surface where the PV cells are installed, it is necessary to calculate the free surface to show if the investment is viable. In aquaculture farms, PV cells can be installed on the barge thus providing the energy needed for operating the farm. For the energy needs of the vessel, a battery is installed that charges during the night from the Norway national grid. This limits the flexibility of vessels as they depend on the charging time and shortens the travel distance due to smaller energy production, compared to the diesel-powered vessel. The second influential factor is the level of solar irradiation.

2.3 Life-Cycle Assessment (LCA)

Life-Cycle Assessment (LCA) investigates the environmental impact of a system and in this paper, it is focused on the emission released throughout its life-cycle. These emissions can be analysed by the following phases [8]:

- WTP (Well-to-Pump) phase – analysis of a fuel cycle (from the extraction of raw material, production of fuel and transport to the refuelling station),
- PTW (Pump-to-Wake) phase – analysis of fuel usage in a power system which causes the tailpipe emissions,
- Manufacturing phase – analysis of the manufacturing process of the main elements in a power system and their related released emissions.

The LCA is performed by means of GREET 2019 software.

2.4 Life-Cycle Cost Assessment (LCCA)

Life-Cycle Cost Assessment (LCCA) includes total life-cycle costs of a system, e.g. investment cost, the cost of fuel, maintenance cost and others. Due to the expected introduction of carbon allowance, i.e. the cost of a permit to emit CO_2, it is useful to calculate the cost-effectiveness of different power system [8].

3. CASE STUDY

The integration of solar technology was shown on the example of a salmon farm in Western Norway (Rogaland county). The farm consists of six cages of the same size, with 150 000 salmons per net cage. The fish is harvested when the salmons have reached a weight of around 4.5 – 5.5 kg [10]. Near the cages, a feed barge is positioned. The barge contains feeders, storage units, cranes, monitoring systems and other equipment needed for daily operations. The total surface area of the barge is 875 m2 and a greater percent could be used for installing PV panels. A vessel was chosen as a reference boat for this case study [11]. The workboat is used for the transportation of workers to the barge and transportation of harvested fish. The LCA and LCCA are performed for a lifetime period of 20 years.

3.1. The LCA of a diesel-powered aquaculture system

Before analyzing solar technology, the environmental impact of the currently used power system configuration is determined. The energy needs for the workboat and for the feeding barge are listed in Table 1.

Table 1 The aquaculture systems main particulars

Workboat	
Fuel consumption daily (kg)	280.00
Energy consumption daily (kWh)	1,302.33
Diesel engine power (kW)	1,480.00
Aquaculture/Barge	
Daily power needs (kWh)	412.65
Daily fuel consumption (kg)	88.71975

The analysis procedure consists of several steps [9]. In the first step, the workboat is investigated to obtain data on daily fuel consumption (FC_{daily}). The energy consumption (EC) is then calculated by dividing the FC_{daily} with the specific fuel consumption (SFC). Since the considered ship is a diesel-powered vessel, the SFC is assumed to be 0.215 kg/kWh. In the last step, the annual emissions are calculated by multiplying the annual fuel consumption (FC_A) with the emission factors (EF):

$$TE_i = FC_A \cdot EF_i \quad (1)$$

where the subscript i refers to any emissions. Then, LCAs and LCCAs are performed for the different scenarios of using the PV system, battery and diesel generator.

The analysis considers emissions released from the diesel engine manufacturing process, the processes of the WTP phase and the PTW phase, shown in Figure 3. All these emissions contribute to the CF of a diesel-powered system. The whole analysis is elaborated in detail by Perčić et al. [8].

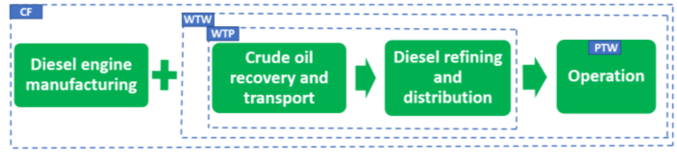

Figure 3 Processes included in the LCA – Diesel Part

The environmental impact of a diesel engine was assessed considering the weight ratios of the material contents in the engine as described by Perčić et al. [8]. The parameters of the material manufacturing process are obtained from the GREET 2019 database.

3.2. The LCA of a solar-powered aquaculture system

Integration of solar power into the aquaculture systems allows us to fully electrify the workboat. Implementing a battery as the only power source onboard leads to the reduction of emissions. Processes included in the LCA of the battery-powered ship are presented in Figure 4. Similar research was conducted for the Croatian short-sea shipping sector [8].

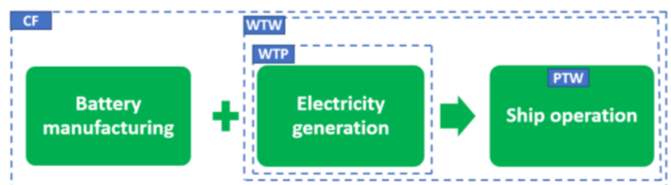

Figure 4 Processes included in the LCA – Battery ship

The battery is charged from the Norwegian power grid. Its capacity needs to be enough to ensure the boat operation and due to safety reasons, the capacity is increased by 20%. The energy characteristics of the electric workboat are shown in Table 2.

Table 2 The electric workboat main particulars

Workboat	
Energy consumption daily (kWh)	1,302.33
Battery capacity	1,562.79
Battery weight (kg)	7,813.95

Regarding the feed barge, a PV system is installed which converts solar energy into electricity, shown in Figure 5. The PV cells are placed on the deck horizontally and, for the specified workboat, the available area is around 744 m^2.

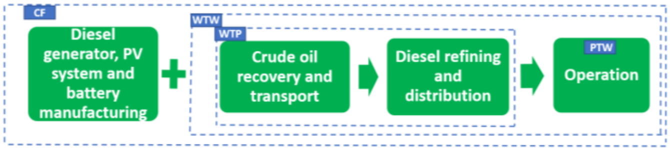

Figure 5 Processes included in the LCA – Solar-diesel generator for aquaculture farm

The power output of a PV system (PPV) depends on its efficiency (η) (17% [2]), and on solar irradiation (E_{rad}), which its annual average value for the area of navigation and the horizontally placed PV cells is equal 4,888 MJ/m2 [10]. The P_{PV} is calculated as follows:

$$P_{PV} = \frac{\eta \cdot E_{rad} \cdot A}{t}. \qquad (2)$$

The battery capacity for the feed barge isn't sufficient to meet the energy needs of the barge. The capacity is calculated by the following formula, with the specific energy of 0.2 kWh/kg:

$$BC = 1.2 \cdot EC. \qquad (3)$$

For that reason, a diesel generator is also installed. The energy balance of the barge is shown in Table 3.

Table 3 Energy characteristic of the barge system

Aquaculture/Barge	
PPV daily (kWh)	78.42
Daily energy needs (kWh)	412.65
Diesel generator consumption daily (kWh)	334.23
Fuel consumption (daily) (kg)	71.86
Battery capacity (kWh)	412.65

3.3. The LCCA of a diesel-powered aquaculture system

The investment cost of a new diesel engine on the workboat is calculated by multiplying the average power of the workboat with the assumed conversion factor of 250 €/kW. The overall cost of the workboat use depends also on the fuel cost and maintenance cost. The fuel cost depends on the diesel cost (for Norway 1.05 €/kg), while the maintenance cost includes the energy consumption and the cost of maintenance of diesel engine (0.0140 €/kWh). Energy consumption remains the same as for the diesel-powered workboat. A similar calculation is made for the feed barge. The investment cost is calculated by multiplying the capital cost of the diesel generator (554 €/kW) with its power (110 kW). Life-cycle fuel cost calculates the annual fuel consumption with the diesel cost. Maintenance cost calculates the power needs and the cost of maintenance of diesel generator.

3.4. The LCCA of a solar-powered aquaculture system

The overall cost of an electricity-powered workboat calculates the life-cycle fuel price (285,209.30 €) and battery costs (investment in the amount of 694,573.64 € and replacement in the amount of 264,111.63 €). The powering of the barge includes several outgoings. The power system consists of a PV system and a diesel generator. The overall cost of the PV system includes investment cost for the battery (917,000.00 €) and PV (121,599.36 €). Maintenance cost for the battery replacement is in the amount of 348,689.25 € and for the PV system 486,397.44 €. The diesel generator requires an investment of 60,940.00 €, life-cycle fuel cost 550,808.75 € and maintenance cost 34,158.68 €.

4. RESULTS

The LCA and LCCA are performed for a diesel-powered and solar-powered aquaculture system. The results are shown in Figure 6 and Figure 7. The results of the LCA show that the electrification of the ship is an environmentally friendly option. A significantly lower level of CF has been achieved. The CF is 96,13% lower in the case of full electrification of the workboat. The results were influenced by the fact that Norwegian electricity mostly originates from RES. Due to that, emissions have lower values. Integrating the solar technology in the aquaculture farm also decreases the CF but visibly less, only 13,01%. However, every reduction in GHGs emission is significant.

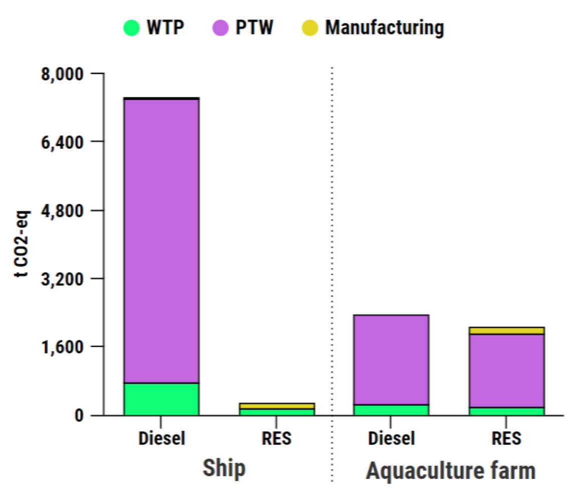

Figure 6 The LCAs results

According to the LCCA results, integrating the RES into aquaculture farm considerably increases the investment and maintenance costs. However, the costs for the fully-electric workboat are reduced by 53%.

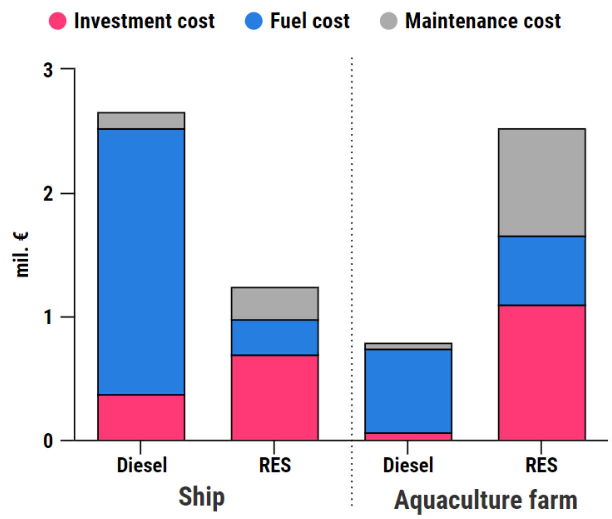

Figure 7 The LCCAs results

5. CONCLUSION

The paper presented the energy needs of an aquaculture farm and an associated vessel. The analysis shows that electrification of a workboat can significantly reduce GHGs and have a positive impact on cost reduction. However, an unfavourable choice of RES may result in high costs and an imperceptible reduction in GHGs. One example of RES integration in aquaculture has been shown and extended research will include other forms of RES related to the maritime environment as well as other types of emissions. The aim is to obtain a complete insight into the integration of RES in aquaculture based on the techno-economic analysis.

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