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Environmental and Energy Performance of Offshore Aquaculture Systems Incorporating with Ocean Renewable Energy Sources

Weiyu Yuan [1,2,3], Jing-Chun Feng [1,2,3*], Si Zhang [1,2], Songwei Sheng [4], Liwei Sun [1,2,3], Chenyao Le [1,2,3]

1 Research Centre of Ecology & Environment for Coastal Area and Deep Sea, Guangdong University of Technology & Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, 510006, China

2 Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, 511458, China

3 School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou, 510006, China (* Corresponding Author)

4 Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510640, China

ABSTRACT

Aquaculture industry continues to grow globally as an increasing need for global food access and security. The corresponding operations for aquaculture are moving to farther offshore areas, pursuing greater productivity. Several new offshore aquaculture systems incorporating with ocean renewable energy sources, have emerged in recent years. However, the environmental and economic effects of these offshore aquaculture systems have not been systematically performed up to now. In this study, a wave powered offshore aquaculture platform, Penghu, was taken as a case study to evaluate the environmental and economic performance using life cycle assessment (LCA) and life cycle cost assessment (LCCA). Additionally, the energy performance of power system on the platform was also discussed. Results showed that the carbon footprint of the aquaculture platform was 2,307 t CO_2-eq. The production operations on the platform achieved zero-carbon emissions, due to all production facilities were entirely powered by renewable energy. Additionally, the energy payback time of the power system was about 0.8 years. The energy payback ratio is 25.23. The LCCA analysis indicated that the profits from this new offshore aquaculture platform is substantial, although the total cost is much higher than that of the conventional system.

Keywords: Marine aquaculture; offshore fishery; ocean renewable energy; life cycle assessment; life cycle cost assessment; carbon footprint

NONMENCLATURE

Abbreviations	
GHGs	Greenhouse Gases
RES	Renewable Energy Sources
CF	Carbon Footprint
PV	Photovoltaic
ORE	Ocean Renewable Energy
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
GIEC	Guangzhou Institute of Energy Conversion
EPT	Energy Payback Time
EPR	Energy Payback Ratio
WEC	Wave Energy Converter
ROVs	Remote Operated Vehicles
Symbols	
BW	Battery weight (kg)
BC	Battery capacity (kWh)
BSE	Battery's specific energy

1. INTRODUCTION

Aquaculture, both land-based and marine-based operations, continues to grow globally as an increasing need for global food access and security. The account of the aquaculture has occupied for 46% of world fish production as of 2018. This expansion coupled with increased competition for space has led to an interest in moving operations to farther offshore areas, pursuing greater productivity. However, the marine aquaculture including operations in coastal/nearshore or offshore areas only makes up a smaller portion of total aquaculture production [1].

Aquaculture system in a marine environment generally consists of net cages, farm vessels needed for work or maintenance, and onshore energy network [2]. Obtaining a continuous and stable energy supply is one of the most important issues for the aquaculture system to move towards farther offshore areas. In addition, more complex operating environment is a limitation for the development of the offshore aquaculture. Therefore, there have only been a small number of cases in offshore areas to date. Note that there is no standard definition of “offshore” aquaculture, although a few studies defined offshore by depth or distance from shore or generally by an environment exposed to ocean waves [3, 4]. The offshore aquaculture is still a novel and evolving aspect of the aquaculture sector.

Some examples of offshore aquaculture include Ocean Farm 1, Deep Blue 1, and Aquatraz. Ocean Farm 1 was designed in China and deployed 30 km off the coast of Norway in 2017, which is the first offshore fish farm. Additionally, Deep Blue 1 was launched in 2018 in China 48 km off the coast in Shandong Province and Aquatraz has been tested in Norway since 2018. A common feature of these offshore operations is that the fossil fuels as the main power source is needed to provide electricity for production equipment in the fish farming process. The case of Deep Blue 1 or Aquatraz is just a giant aquaculture cage, where there is no corresponding fishery production equipment. Typically, production equipment such as automated feeders, sensors, monitoring systems, and cranes is integrated on a barge for the implementation of feeding, monitoring, and other operations. The energy supply for the barge and the corresponding equipment on it relies on diesel generators [3]. As the aquaculture industry continues to expand globally and the scale of offshore operations continues to grow, however, it will lead to higher energy needs of offshore aquaculture farm worldwide. The conventional energy supply by burning fossil fuels will generate a large amount of greenhouse gases (GHGs), which puts the offshore aquaculture systems at a disadvantage when it comes to coping with climate change [5].

Replacing fossil fuels with renewable energy as the main energy source for mariculture has been proposed. Koričan et al. [6] considered the use of renewable energy sources (RES) in mariculture systems to ensure low carbon footprint (CF) in farming process. The different power system configurations were considered to integrate on the work boat in their study, including diesel-powered, battery-powered, and wind-photovoltaic (PV) cells powered systems. The results showed a GHG emission reduction of about 20% and an increase in capital costs by 0.61% with the implementation of RESs in mariculture systems.

There will be greater potential for mariculture to utilize ocean renewable energy (ORE), when operations are shifted farther offshore areas. Internationally, a few case studies have demonstrated the technical feasibility of ORE to provide necessary energy needs for offshore aquaculture systems. In China, a semi-submersible offshore aquaculture platform powered entirely by ORE was put into operation in 2019 [7]. Aquaculture net cages, fishery production equipment, and energy system were all integrated into the semi-submersible platform. This design perfectly solved the difficulty of energy supply for production operations in offshore areas. In addition, the organic integration of ORE generation, deep-water aquaculture, aquaculture vessels and other technologies, has greatly reduced the energy requirements and enhanced the cleanliness for offshore aquaculture systems. Nevertheless, the research or pilot projects for co-locating ORE and offshore aquaculture have not been carried out on a large scale. The environmental and economic effects of offshore aquaculture incorporating with ocean RES have not been systematically performed up to now. The environmental and economic assessment of mariculture systems using a high share of RES has already been conducted by Koričan et al. [6], however, the farming pattern mentioned in their study is not much different from the conventional operations (see Fig.1). Moreover, the focus in their study is on the GHG emissions related to the power system, which is not entirely made up of RES. The environmental and economic benefits of offshore aquaculture from fully integrating fishery production technologies into a system and fully using ORE to provide electricity, are not comprehensively performed.

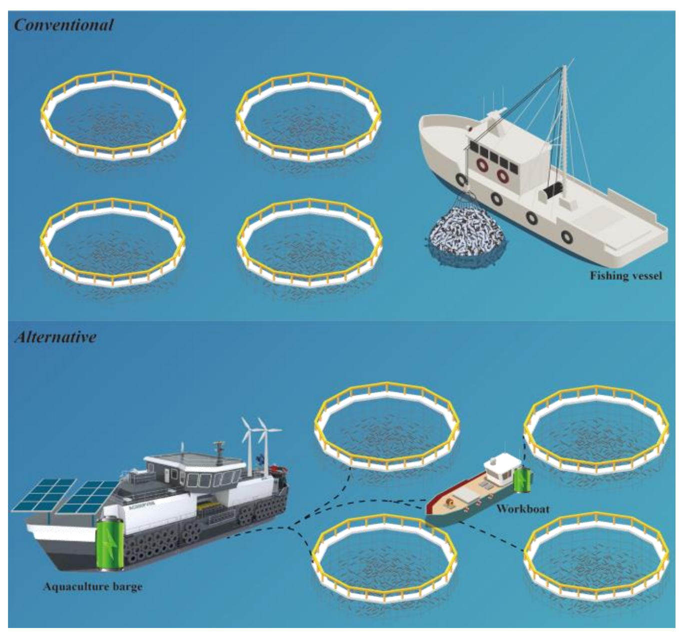

Fig. 1 Traditional farming pattern versus the alternative mentioned by Koričan et al. [6]. | In the alternative, the production equipment is re-located onto an aquaculture barge, reducing the demand of diesel-powered vessels. The workboat is used for the transportation of workers to the barge and transportation of harvested fish.

In this study, an offshore aquaculture system fully supported by clean energy and integrated with multiple technologies was discussed in detail. The environmental and economic performance of the system was analyzed by performing life cycle assessment (LCA) and life cycle cost assessment (LCCA). Additionally, the energy performance of power system on the platform was also discussed. The analysis was conducted by taking a semi-submersible wave energy aquaculture platform as a case study, which was developed by Guangzhou Institute of Energy Conversion (GIEC), Chinese Academy of Sciences.

2. METHODS

2.1 Life cycle assessment

The LCA method was used to investigate the environmental impact of the offshore aquaculture system. In this study, the focus is on the GHG emissions of the aquaculture system released from cradle to gate. These emissions were analyzed by the following three stages: (1) Manufacturing of platform and related equipment, (2) Platform towing by tugboat, and (3) Fish farming process. The online LCA evaluation system, eFootprint, was used to calculate the emission intensity of each stage.

2.2 Life cycle cost assessment

The LCCA refers to an analysis of the total lifecycle costs of a system, such as investment cost, operating costs, maintenance cost and others. Due to the expected introduction of carbon allowance in the future, i.e., the cost of a permit to emit CO_2, it is useful to calculate the cost-effectiveness for the offshore aquaculture system [6].

2.3 Energy performance

Energy payback time (EPT) and energy payback ratio (EPR) were calculated in this study, which are the two common energy indicators for renewable electricity generation. EPT expresses the amount of time in months or years, taken to “pay back” the energy invested in infrastructure and extraction/transport processes. EPR is used to evaluate whether a power system produces more energy than it consumes during its life cycle, which can be expressed using the following equation [8]:

$$EPR=Lifetime/EPT \quad (1)$$

2.4 Data source

The data used to implement LCA and LCCA were obtained through on-site survey and interviews with relevant staffs.

3. CASE STUDY—PENGHU AQUACULTURE PLATFORM

With government support for using ORE for aquaculture in China, the co-location of ORE facilities and fish farms has been implemented recently. Penghu, a semi-submersible platform integrated with a wave energy converter (WEC) and solar PV power system for offshore aquaculture, was designed by GIEC. This platform, 66 m long, 28 m wide and 16 m high, was launched in the sea area off Zhizhou Island in Zhuhai, Guangdong Province in 2019 for finfish aquaculture. As mentioned earlier, the aquaculture net cages, fishery production equipment and basic living facilities are all integrated in the platform. Daily production and life are completely powered by the 60 kW of wave energy and 60 kW of solar energy. 15,000 m^3 of aquaculture space and 300 m^3 of storage space can be provided by the platform. More characteristics and information were summarized in Table 1. Fig.2 shows the Penghu wave powered aquaculture platform.

Table. 1 Overview of the characteristics of Penghu aquaculture platform.

Characteristic	Parameter
Distance to shore [km]	30
Water depth [m]	20
Weight (including the equipment on the platform) [t]	1,600
Aquaculture space [m^3]	15,000
Power system:	
-Solar PV cells [kW]	60
-WEC [kW]	60
-Lithium battery [kWh]	500
-Generating capacity [kWh/day]	400
Lifetime [years]	20

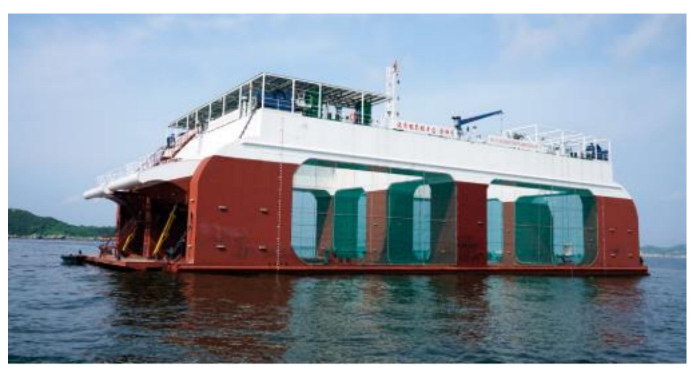

Fig. 2 Penghu semi-submersible wave powered aquaculture platform (image courtesy of Guangzhou

Institute of Energy Conversion, Chinese Academy of Sciences).

3.1 LCA analysis

At present, the core function of this semi-submersible platform is fish farming. Therefore, 1 ton of finished live fishes produced by the platform was chosen as the functional unit. A simplified overview of system boundary can be seen in Fig.3.

Including all equipment integrated on the platform, 1,600 t of steel was consumed for Penghu platform. The PV cells were installed on top of the platform, occupying 400 m2. The weight of the energy storage battery on the platform can be calculated using equation (2) [6]:

$$BW=BC/BSE \tag{2}$$

Where *BW* is the weight of the battery in kg; *BC* represents the battery capacity in kWh; *BSE* represents the battery's specific energy, which was assumed as 0.25 kWh/kg in this study.

The platform was towed to the target sea area by tugboat after finishing manufacturing in the shipyard, which took 8 hours. During transportation, the fuel oil consumption was assumed as 596 l/h in this study [9]. According to the suggestion of fry supplier, 15 juvenile fishes per cubic meter were assumed to be raised in the net cage. The weight of each fry was assumed as 50 g. As the platform provides 300 m^3 of feed storage space, the frequency of feed replenishment can be reduced during the period of farming. The current replenishment frequency is once every two weeks according to the staff. Additionally, light trapping is used to attract surrounding fishes into the cage for the farmed fish to eat, due to the large operating space of the platform as well as the continuous and stable power output. This operation can reduce the feed input, realizing that only one catty of feed is needed to make the fish grow two catties of flesh.

The platform operates normally after being put into use. There was no fish disease or death in the aquaculture cycle. In addition, no major maintenance operations have been conducted since the platform was launched in 2019. Usually, only remote operated vehicles (ROVs) and divers are used for net cage inspection and repair work. The consumption in terms of maintenance is extremely small, and the operation process does not involve fuel use. Moreover, 90% of the steel was considered to be recycled at the end of the lifetime.

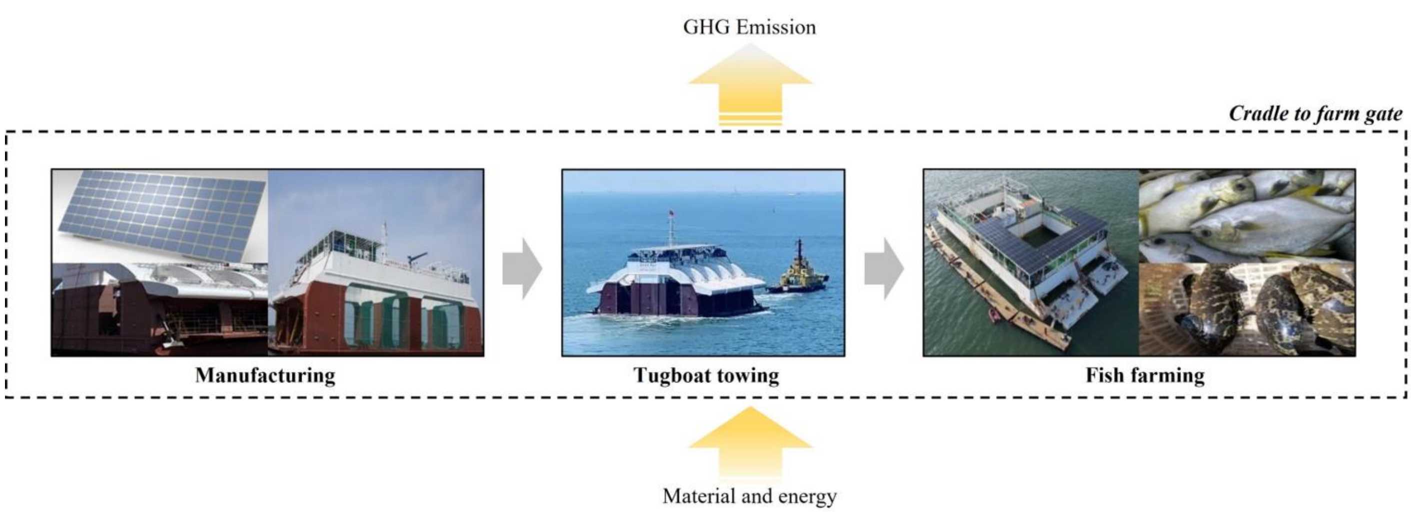

Fig. 3 System boundary of the semi-submersible wave powered aquaculture platform.

3.2 *LCCA analysis*

For this new aquaculture model, the overall cost is focused on the platform manufacturing. Since all equipment and power system were integrated into the platform as it was manufactured, transportation and installation costs can be greatly reduced. The investment cost of the platform is 10 million RMB. Additionally, the cost of feed input is also reduced to a large extend with the help of light trapping. Intelligent operations make management cost low in the aquaculture process. Typically, only one person is needed for the daily management of the platform. Routine inspection and repair of net cages can be done by one person, and the frequency is generally once every two months. During operation, fuel costs only occur in the replenishment process, as all energy demand of the platform can be fully self-sufficient by ORE. Generally, it takes about 16 liters of fuel oil to make a round trip for the replenishment, according to the crew.

4. RESULTS AND DISCUSSION

4.1 *Carbon footprint of the baseline case and energy performance for the power system*

As shown in Fig.4a, the largest contribution to the GHG emissions was the platform and equipment manufacturing, accounting for 82.03%. One of the main reasons is that the manufacture phase is an energy intensive process. The required power comes from land-based electricity grid. Although the proportion of renewable energy in the grid is gradually expanding, fossil energy is still dominant at present. Additionally, feed production was another major source of GHG emissions for the offshore aquaculture system, accounting for 16.54% of the overall emissions. It is worth mentioning that the emissions of the fish farming process only accounted for 0.06%. These emissions were mainly from the transport for supplements and fishes. The production operations on the platform were zero-carbon emissions. This owed to the fact that all production facilities were entirely powered by ORE. The CF of the Penghu was about 2,307 t CO_2-eq. Compared with the alternative and conventional patterns studied by Koričan et al. [6], this value has been reduced a lot. The low CF of the Penghu illustrated that the offshore aquaculture system completely integrated with ORE system has much better environmental performance.

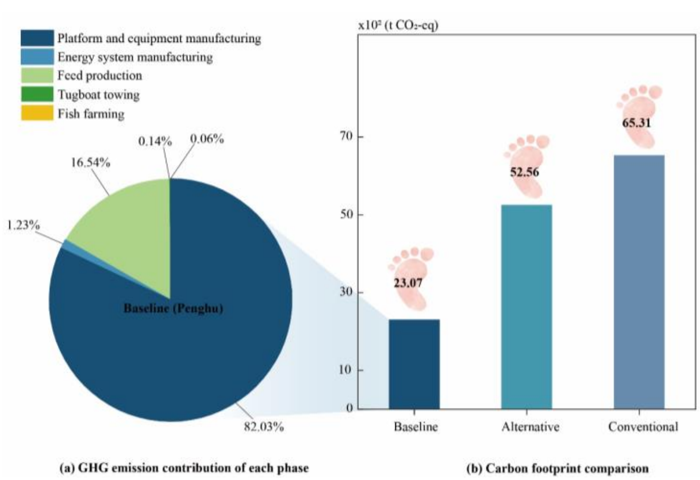

Fig. 4 LCA results of the baseline case and the comparison with other mariculture systems.

The EPT of the ORE system was about 0.8 years. This means that the energy consumed during the lifetime of the power system can be compensated after about nine months of operation. The EPR was 25.23, indicating the power generation capacity of this ORE system was relatively optimistic during operation.

4.2 *LCCA results*

Fig.5 showed that the cost of the offshore aquaculture system is much higher compared to the conventional patten and alternative. The investment cost of the platform accounted for 73.1% of the total cost. Followed by the operation cost, it accounted for 26.8%. Feed is the largest expense during the operation period. However, it is obvious that the higher profits from the Penghu, compared to the other pattens. According to the staff, the current profit of the Penghu reached about 20 million RMB per year. The costs and profits of the alternative proposed by Koričan et al. [6] is not much different from the conventional mariculture system.

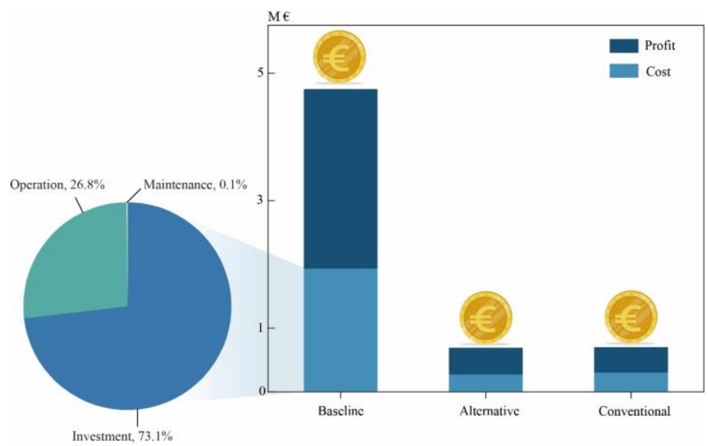

Fig. 5 LCCA results of the baseline case and the comparison with other mariculture pattern.

5. CONCLUSION

In this study, the environmental and economic performance of an offshore aquaculture platform incorporating with ORE, was analyzed by performing LCA and LCCA. The energy performance of the ORE power system on the platform was discussed. The main conclusions can be drawn as follows:

(1) The LCA analysis indicated that the CF of the baseline case (Penghu) was 2,307 t CO_2-eq, which is much lower compared to the conventional patten and alternative. The platform manufacturing and feed production accounted for 82.3% and 16.54% of total life cycle GHG emissions, respectively. The production operations on the platform achieved zero-carbon emissions, due to all production facilities were entirely powered by ORE.

(2) The EPT of the ORE system was about 0.8 years, and the EPR is 25.23, indicating a relatively optimistic energy performance for the wave and PV powered aquaculture platform.
(3) The LCCA analysis indicated that the cost of the offshore aquaculture system is much higher compared to the conventional patten and alternative. The investment and operation cost accounted for 73.1% and 26.8%, respectively. The profits from this new offshore aquaculture system were substantial.

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REFERENCE

[1] FAO (Food and Agriculture Organization). The State of World Fisheries and Aquaculture 2020. 2020.
[2] Aubin J, Papatryphon E, Van der Werf HMG, Petit J, Morvan YM. Characterisation of the environmental impact of a turbot (Scophthalmus maximus) re-circulating production system using Life Cycle Assessment. Aquaculture. 2006;261:1259-68.
[3] Chu YI, Wang CM, Park JC, Lader PF. Review of cage and containment tank designs for offshore fish farming. Aquaculture. 2020;519.
[4] Taelman SE, De Meester S, Schaubroeck T, Sakshaug E, Alvarenga RAF, Dewulf J. Accounting for the occupation of the marine environment as a natural resource in life cycle assessment: An exergy based approach. Resources Conservation and Recycling. 2014;91:1-10.
[5] Feng JC, Yan J, Wang Y, Yang Z, Zhang S, Liang S, et al. Methane mitigation: Learning from the natural marine environment. Innovation (Camb). 2022;3:100297.
[6] Koričan M, Perčić M, Vladimir N, Soldo V, Jovanović I. Environmental and economic assessment of mariculture systems using a high share of renewable energy sources. Journal of Cleaner Production. 2022;333.
[7] OES (Ocean Energy Systems). Offshore aquaculture: A market for ocean renewable energy. 2022.
[8] Raadal HL, Vold BI, Myhr A, Nygaard TA. GHG emissions and energy performance of offshore wind power. Renewable Energy. 2014;66:314-24.
[9] Garcia-Teruel A, Rinaldi G, Thies PR, Johanning L, Jeffrey H. Life cycle assessment of floating offshore wind farms: An evaluation of operation and maintenance. Applied Energy. 2022;307.