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Techno-Economic Analysis of a Marine Aquavoltaic System in Iran

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Abstract. In oil-rich countries such as the Middle East, the affordability and viability of renewable technologies and resources is hampered by the accessibility and low cost of fossil fuel resources. This represents a significant barrier to the progress and acceptance of renewable energy. The use of aquavoltaics is one of the creative measures that can solve the land and food problem and increase the attractiveness for investors. In this method, the simultaneous integration of the two systems of fish farming and photovoltaics, both of which play a crucial role in providing food security and sustainable energy, partially solves the problems of the two systems when implemented separately. The results of this research have shown that the aquavoltaic system has an annual profit of 42.32% and within 4 years the initial investment cost is returned to the investor. In addition, the aquaculture system produces 498.48 kg of Salmo Salar fish annually and the floating photovoltaic system, which consists of thin-film modules, feeds 300.85 MWh of energy into the power grid annually. The considerable profitability and shorter payback period of this project compared to the interest rates offered by Iranian banks to depositors, as well as the results of previous studies, have prompted investors to support this initiative. This in turn has encouraged the expansion of renewable energy and reduced dependence on fossil fuels.

Keywords: Aquavoltaic, Aquaculture, Floating PV

1. Introduction

Global demand for fish and seafood is increasing at an estimated annual growth rate of 1.5% due to population growth, urbanization and rising income levels [1]. In order to expand aquaculture production, both the intensification of existing facilities and the construction of new facilities are required. However, this leads to increased competition for resources such as space, water, energy and feed. To solve this problem, innovative strategies such as aquavoltaics are gaining increasing attention [2]. In oil-rich countries such as the Middle East, the affordability and viability of renewable technologies and resources is hampered by the accessibility and low cost of fossil fuels. This is a significant barrier to the progress and adoption of renewable energy [3]. The use of aquavoltaics is one of the creative measures that can solve land and food challenges and increase the attractiveness for investors. In this method, the simultaneous integration of the two systems of fish farming and photovoltaics, both of which play a crucial role in providing food security and sustainable energy, partially solves the problems of the two systems when implemented separately. Salmo salar, commonly known as Atlantic salmon, is one of the most economically significant fish species in global aquaculture. It is highly valued for its nutritional benefits and is a major commodity in the seafood market [4]. In countries with growing aquaculture sectors like Iran, introducing Atlantic salmon could enhance economic growth and nutritional benefits. Exploring the potential for Atlantic salmon farming in Iran could align with global trends and strengthen the local seafood market's economic and nutritional contributions.

2. Method of research

The aquavoltaic system of this research is a floating photovoltaic system consisting of thin-film solar modules and an aquaculture farm where Salmo Salar fish are bred. Figure 1 shows the proposed schematic of the aquavoltaic system in this study. According to this figure, six Salmo Salar fish farming cages are placed in the sea and the thin-film solar modules are placed floating between the cages, so that 4 floating photovoltaic solar power plants are used in the system. The technical modeling of the aquaculture system includes the amount of fish harvested and the amount of electrical energy fed into the grid. When examining the economic variables of the aquavoltaic system, in addition to calculating the economic parameters, the annual profitability of this system is also compared with the interest rate that Iranian banks pay to depositors.

2.1 Aquaculture system modeling

The technical modeling of fish farming is divided into 2 steps. In the first step, each fish is bred individually to reach the desired weight, and in the second step, the total weight of the harvested fish in each farm and the number of cycles in the entire breeding period are calculated according to the assumptions mentioned in Table 1. The FinFish Aquaculture software from the InVEST™ software collection can be used to model the aquaculture system.

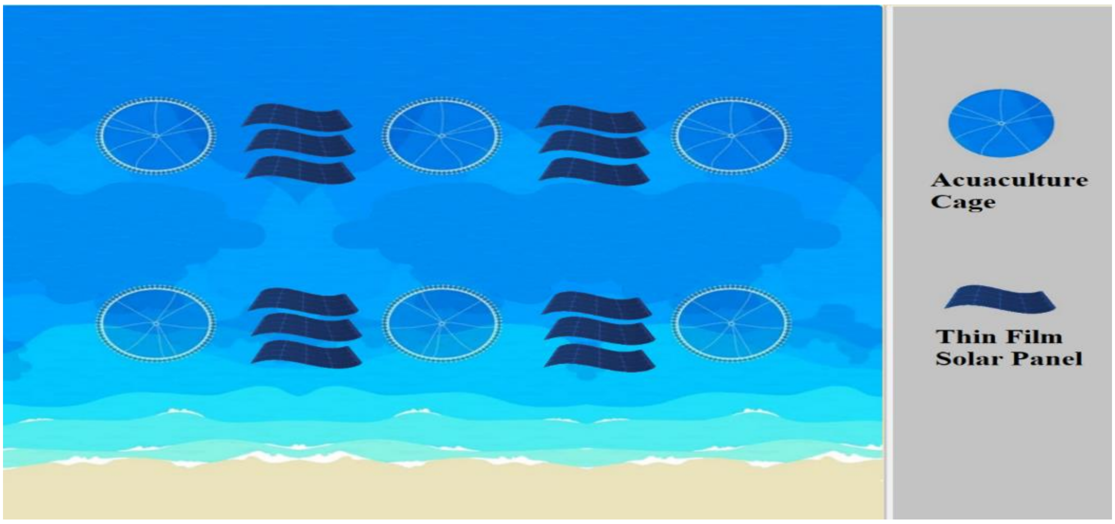


Figure 1. *The proposed scheme of the aquavoltaic system.*

- First step, modeling the growth of each fish to reach the final weight:

In the first step, the weight of the desired fish is modeled from the time it is released into the cage until the time it is harvested. Equation 1 is used to calculate the weight of each fish under the influence of daily temperature and growth parameters [5].

$$W_{t,y,f} = \left(aW^{b}{}_{t-1.y.f} . e^{\tau . T_{t-1,f}} \right) + W_{t-1,y,f} \tag{1}$$

W: Weight of each fish [kg]	α & β: Fish growth parameters [g/day]
T: Day number [-]	T: Water surface temperature [°C]
Y: Year [-]	T: Temperature reversal [1/°C]
F: Fish Farm Number [-]	$W_{t-1,y,f}$: Fish weight at the release time in the cage [kg]
$W_{t,y,f}$ = Final weight of each fish [kg]	

At this stage of the modeling, the initial weight of the juvenile fish placed in the cage is 60 grams, with a target growth to 1 kg. The model assumes a 20-year operational period with a stock of 600 fish. Second step; Evaluation of the total weight of fish harvested from a farm

To calculate the total weight of fish produced in each farm, it is assumed that there are no differences between the fish and that all fish have reached the desired size at the time of harvest. Equation 2 shows the calculation of the total weight of fish produced in each farm in each cycle. Of course, this weight is calculated by subtracting the daily natural mortality of the fish, which is calculated for each cycle [5].

$$TPW_{f.c} = W_{th,h,f} . d . n_f e^{-M.(t_h - t_0)} \tag{2}$$

TPW: Total weight of processed fish [kg]	$W_{th,h,f}$: Final weight of the fish at the time of harvest [kg]
n_f: Number of fish per farm [-]	d: Fraction of weight of fish that remains after cleaning the fish [%]
$e^{-M.(t_h - t_0)}$: Daily natural mortality rate of fish from the beginning of the cycle until the fish reach the final weight [-]	M: Experimental number for each fish species [-]

***Table 1**. Assumptions used in aquaculture system modeling.*

α	β	τ	n_f	d	M
0.038	0.6667	0.08	600	0.85	0.000137

2.2 Choosing the optimal location

The choice of the optimal location for this project is very important. Factors that influence the choice of the optimal location for the aquavoltaic system include seawater temperature, chlorophyll a and the salinity of the water. Changes in water temperature affect the metabolism and activities of the fish, oxygen consumption and fish growth [5]. The optimal temperature range for the growth of Atlantic salmon (Salmo salar) is between 6°C and 22.5°C, with the ideal temperature being approximately 15.9°C [6]. At temperatures around 22°C, salmon begin to exhibit signs of stress, while temperatures between 25°C and 28°C are considered lethal [7]. Consequently, aquaculture facilities should be strategically located in areas where water temperatures remain consistently below these critical thresholds during the rearing period. Measuring water parameters such as water surface temperature, chlorophyll a and water salinity using conventional methods is very time-consuming and costly. In recent years, remote sensing technology and the use of research satellites have emerged as one of the most important tools for determining water surface temperature and water chlorophyll, and there is an increasing trend in studies related to the oceans. To this end, to measure the temperature of seawater and chlorophyll a, the MODIS sensor images from the Terra satellite (NASA) were extracted via the Google Earth Engine system and analyzed using the SeaDAS software. The SMOS satellite was also used to measure the salinity of the water. According to Figure 2-,, it can be concluded that the northeastern shores of the Caspian Sea, particularly the waters of the

Gomishan region in Iran, are optimal locations for establishing an aquaculture system. This region's water temperature is lower than other parts of the Caspian Sea and the Persian Gulf, making it more suitable for rearing Salmo salar. The lower temperatures stay well below the lethal threshold for the fish, minimizing mortality risk. Furthermore, as shown in Figure 4, the Gomishan region has the lowest salinity and chlorophyll content along the Caspian Sea coast, reducing the likelihood of phytoplankton blooms. These environmental advantages, combined with the potential for fostering aquaculture as an emerging industry in Iran, make the Gomishan region an ideal choice for the project.

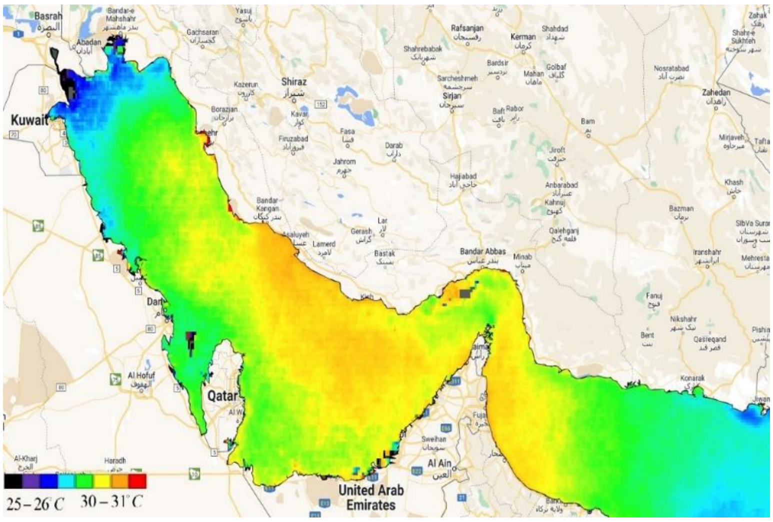


Figure 2. *Satellite image of Persian Gulf water temperature*

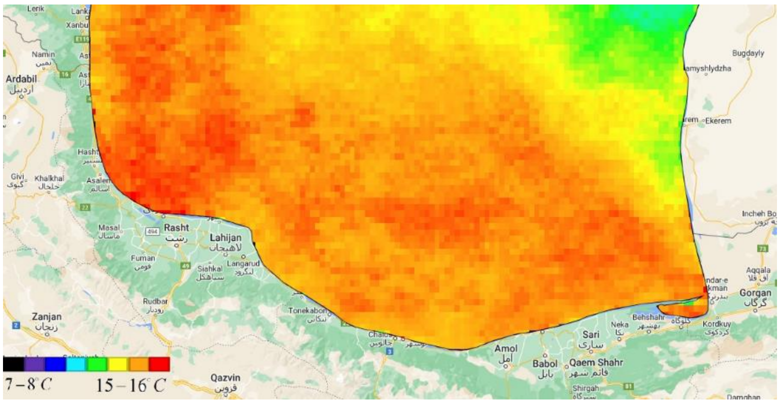
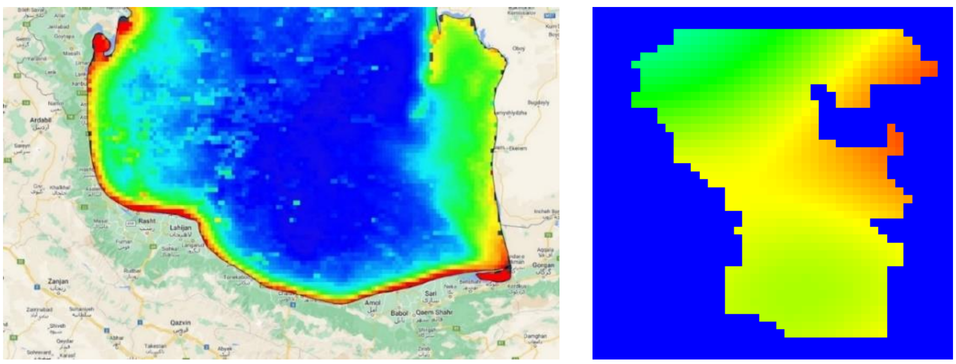


Figure 3. *Satellite image of Caspian Sea water temperature*



(a) *(b)*

Figure 4. *Satellite image of the Caspian Sea, (a) chlorophylla concentration and (b) sea water salinity*

2.3 Modeling of floating photovoltaic system

Based on Lerang's research, it was found that when modeling a floating photovoltaic power plant, the PVsyst software simulates the cell temperature more correctly than the TRNSYS software [8]. PVsyst software was used for modelling the floating photovoltaic system in this study. The floating photovoltaic system of this study is a system with a capacity of 196 kW, consisting of 4 power plant units of 49 kW, and its technical data are shown in Table 2.

Table 2. *Assumptions used in Floating PV system modeling.*

Type of equipment	Equipment Brand	Degree Of Protection	Equipment model	Type of Panel	Efficiency
Solar Panel	TSMC Solar	IP=67	TS-150C1	CIGS Thin Film	13.8%
Inverter	Huawei Technologies	IP=65	SUN2000-40KTL	-	98.9%

2.4 Economic analysis of aquavoltaic system

To analyze the profitability of an aquavoltaic project, engineering economic indicators such as net present value (NPV), payback period (PBP) and investment return rate (IRR) for floating photovoltaic systems and fish farms must be examined. Industry and company managers tend to use the IRR index to compare projects of different sizes, as it is easier to compare projects of different sizes with a single percentage [9]. Due to the complexity of the calculations, the Excel software can be used to analyze the economic variables of the aquavoltaic project, while the RETScreen software can be used to analyze the economic variables of the floating photovoltaic system. The economic calculations for the aquavoltaic system are based on the assumptions listed in Table 3. This table and the assumptions used for the aquavoltaic project were prepared based on the instructions announced by the government of the Islamic Republic of Iran.

Table 3. *Assumptions used in economic analysis of aquavoltaic system.*

Electricity export escalation rate	Tax holiday duration	Effective income tax rate	Discount rate	Inflaction rate
12%	10 year	30%	19%	23.3%

3. Results and discussion

3.1 Technical analysis of aquaculture system

The first step in analysing the aquaculture system in the FinFish software is to select the best day to start the fish farming cycle. Since Salmo salar is a cold water fish and the 60 gramme fry cannot tolerate high heat at the beginning of the cycle, the cycle must start in the cold seasons. Figure 5, which shows the water temperature in the Gomishan region on a daily basis, shows that the water temperature in the Gomishan region is lowest in December, which is the best month to start the fish breeding cycle.

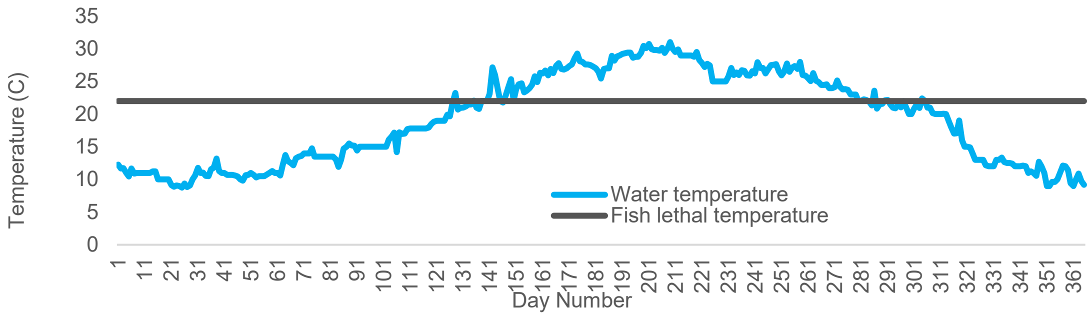


Figure 5. *Daily water temperature chart of Gomishan water area*

Table 4 shows the results of the simulation of the aquaculture system with the Finfish software for one year. Considering that the water temperature during the fish rearing cycle should never exceed the lethal limit for Salmo Salar and that it takes about 171 days for the fish to reach the desired weight, the best day to start the fish rearing cycle is estimated to be the 320th day of the year according to Figure 5 and through trial and error and numerous simulations with the FinFish software, because if the start of the fish rearing cycle is on the 320th day of the year, the fish will not reach the desired weight.

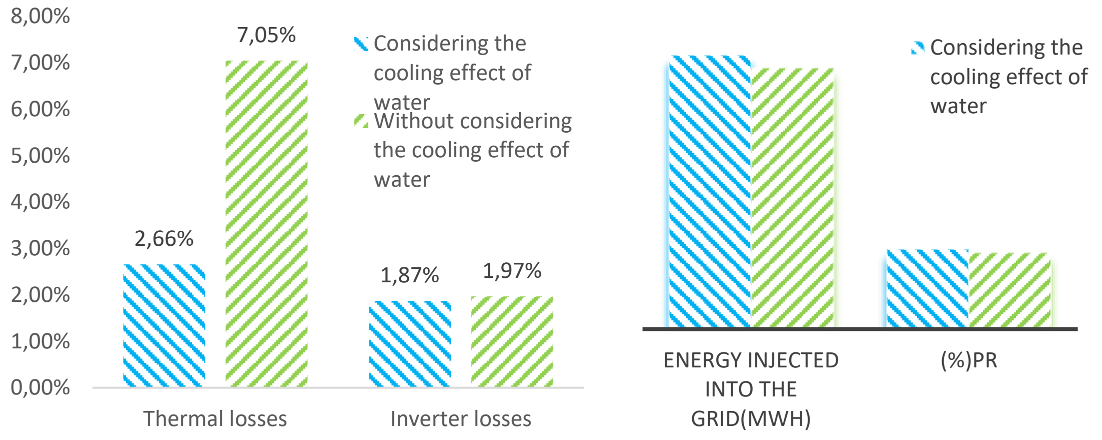
Table 4. *The results of aquaculture system modeling.*

Farm Number	Year Num-ber	Cycle Number	Cycle start day	Cycle end day	Cycle Dura-tion(day)	Weight of Cleaned Fish (kg/cycle)
1	1	1	320	491	171	498.48

Table 4 shows that it takes 171 days each year for the fish to reach the target weight and that the farms are practically empty on the 320th day of the year and at the beginning of the second cycle of fish farming. The fish farms cannot be used in the summer season due to the high heat and rising water temperature, as the temperature exceeds the lethal limit for Salmo salar fish (22°C) and fish losses may occur. In general, 498.48 kg of cleaned Salmo salar fish are harvested annually from each fish farm in this modeling.

3.2 Technical analysis of the floating photovoltaic system

One of the main factors that reduce the efficiency of photovoltaic modules is excessive heat caused by excessive solar radiation and high ambient temperatures. Overheating drastically reduces the efficiency of the panels and increases losses [10]. Figure 6 shows a comparison between the photovoltaic system with and without water cooling. These diagrams show that due to the solar modules floating on the water surface and taking into account the reduction in heat losses due to the proximity of the modules to the water, the temperature losses of the system have been significantly reduced. This reduction in temperature losses has led to an increase in the efficiency of the system and ultimately to an increase in the energy fed into the grid.



(a) (b)

Figure 6. *Comparative diagram of the impact of taking the cooling effect of water into account in the losses (a) and performance (b) of the floating photovoltaic system*

3.3 Economic analysis of the aquavoltaic system

To analyze the economic justification of the aquavoltaic system, the economic variables for aquaculture, floating photovoltaics and aquavoltaic systems were examined and the results presented in Table 5. The positive net present value (NPV) of all three systems shows the economic viability of the project, and the IRR of all three systems also shows the profitability of the systems and the aquavoltaic system of this research.

Table 5. *The results of the economic analysis of the aquaculture system.*

Type of system	Pay Back Period (year)	IRR (%)	NPV
Aquaculture	1.4	260.1	685588
Floating Pv	5.2	24.71	35004
Aquavoltaic	4	42.32	856213

The synergy between the aquaculture system and the FPV system has shortened the payback period of the aquavoltaic system and the strengths of each system have compensated for the weaknesses of the other, taking a big step towards a sustainable energy and food supply. The results of the current investigation are compared with the investigation of Wen et al. [11], which was most similar to the current investigation. It can be seen that despite the fact that there are few studies on the economic analysis of the aquavoltaic system, the current study was able to facilitate the investor's decision for an aquavoltaic project by exploiting the overlap of the weaknesses and strengths of fish farming and floating photovoltaic systems.

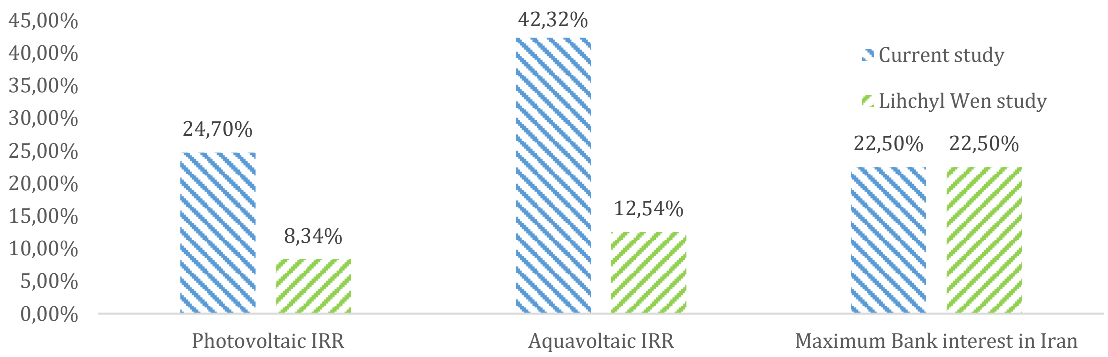


Figure 7. *Comparison of the results of the current study with the study by Wen et al. [11]*

Assuming an interest rate of 22.5% offered by Iranian banks to depositors, the aquavoltaic project demonstrates approximately 19.82% higher profitability compared to the bank interest rate. Additionally, it offers 29.78% more profit annually than the findings reported in Wen's research [11], making it a highly attractive investment for stakeholders. In addition to the profit from the sale of the aquavoltaic system's products, this project will also contribute to sustainable development, expand the use of renewable energy and reduce dependence on fossil fuels by generating solar power without emitting a particle of pollution.

4. Conclusion

In order to investigate the technical and economic aspects of a marine aquavoltaic system in Iran, this study used remote sensing satellite images to select the best site for the construction of the aquavoltaic system in the Gomishan region of the Caspian Sea. Furthermore, the results showed that the aquaculture system produces 498 kg of fish per year and the floating photovoltaic system feeds 300.85 MWh of energy into the grid annually. In addition to a positive NPV, the analyzed aquaculture project achieves an annual profitability of 42.32% and a payback period of approximately 4 years. These results demonstrate that the system is not only economically viable but also significantly more profitable than the 22.5% interest rate offered by Iranian banks to depositors.. In addition, this research has shown that the use of thin-film solar modules near the water increases the efficiency of the floating photovoltaic system due to the reduction of heat losses.

This study concludes that the strengths of aquaculture and floating photovoltaic systems compensate for each other's weaknesses and that the weaknesses of the systems are balanced out by the synergy between aquaculture and floating photovoltaics.

Author contributions

Amin Momeni: Methodology, Software, Writing - Original Draft **Shiva Gorjian:** Conceptualization, Writing - Review & Editing, Supervision **Barat Gobadian:** Writing - Review & Editing, Supervision

Competing interests

The authors declare that they have no competing interests.

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